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Review

A review of dietary polyamines: Formation, implications for growth and health and occurrence in foods

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Abstract

The polyamines putrescine, spermidine and spermine commonly occur in the cells of living organisms where they fulfil an array of physiological roles. Their participation in human cell growth and proliferation has been of great interest for their role in tumour growth. However, polyamines could be useful for post-operation patients, during wound healing and for growth and development of the neonate digestive system. Both endogenous and dietary polyamines participate in such processes. Data on polyamine contents in foods are limited and diffused in literature and dieticians have thus limited plausible information. This review briefly summarizes current knowledge on the biological implications of dietary polyamines for human health and collects the data on their formation and contents in manifold foods. While putrescine content increases by bacterial activity during inappropriate storage and processing of foods of animal origin, spermidine and spermine originate mainly from raw materials. Higher contents of spermidine as compared to spermine are typical for foods of plant origin, while an opposite relation is characteristic for foods of animal origin. The highest contents of all polyamines were determined in cheeses, mainly in ripened types. High putrescine levels were reported in citrus fruits and juices, sauerkraut, ketchup, fermented soybean products and fish sauce. Legumes, cauliflower and broccoli are foods with high spermidine content, while meat, meat products and legumes are high in spermine. Commonly, polyamine contents range widely within the individual food items. Extensive research is needed to extend the current limited database.

Keywords: Polyamines; Putrescine; Spermidine; Spermine; Foods

Contents

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1. Introduction

Putrescine (1,4-diaminobutane), spermidine (*N*-(3-aminopropyl)-1,4-diaminobutane) and spermine (*N*,*N*′-bis-(3-aminopropyl)-1,4-diaminobutane) (Fig. 1) form a group of polycationic amines referred to as physiological polyamines. Traditionally they have been classified within the group of biogenic amines. However, particularly due to their specific biological roles in eucaryotic cells they are now becoming set apart as a peculiar group. Among their biological roles, the participation in cell growth and proliferation has been of extraordinary interest, as polyamines, both formed endogenously and taken from diet, can be involved in tumour development. Medical and physiological research of polyamines has thus been very dynamic. However, data on the formation and content of dietary polyamines in foods have been relatively scarce and diffuse in the literature.

The aim of the article is to review briefly current knowledge on biological implications of dietary polyamines for human health and to collect data on polyamine formation and contents in foods.

2. Polyamines formation and catabolism

Polyamines are ubiquitous constituents occurring in microbial, plant and animal cells. Mammalian biosynthetic pathways were reviewed by Hillary and Pegg (2003). Their biosynthesis (Fig. 2) is very highly regulated by the activities of two key enzymes, ornithine decarboxylase (ODC) and *S*-adenosylmethionine decarboxylase (AdoMetDC) and polyamines are formed from methionine and arginine. The major pathway for putrescine formation in mammalian cells is via the activity of ornithine decarboxylase. Methionine provides the aminopropyl groups needed to convert putrescine into the higher polyamines. The synthesis is carried out by two aminopropyltransferase enzymes, spermidine synthase and spermine synthase.

Plants and many microorganisms can also produce putrescine via the activity of arginine decarboxylase (ADC). However, dietary arginine does not appear to be essential for the maintenance of the homeostasis of free polyamine levels in adult mice, which emphasises the importance of endogenous arginine synthesis in preserving the polyamine body pool (Teixeira, Santaolaria, Meneu, & Alonso, 2002).

In normal healthy cells, polyamine levels are intricately controlled by the biosynthetic and catabolic enzymes (Mitchell, 2003). The latter enzymes include spermidine/spermine acetyltransferase, flavin-containing polyamine oxidase (PAO), copper containing diamine oxidase (DAO), and possibly other amino oxidases.

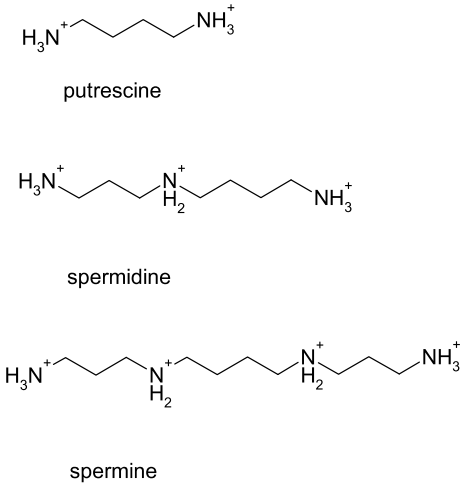

Fig. 1. Formulae of polyamines.

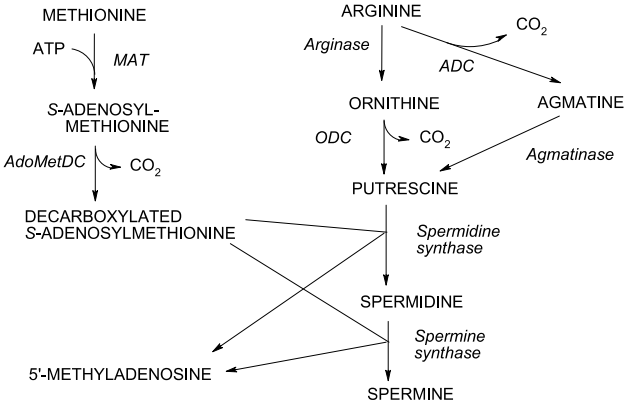

Fig. 2. Mammalian polyamine biosynthetic pathway (adapted from Hillary & Pegg, 2003). The pathway via agmatin, existing in plants, has been proposed also for mammals. The enzymes are written in italic (ADC, arginine decarboxylase; AdoMetDC, *S*-adenosylmethionine decarboxylase; MAT, methionine adenosyltransferase; ODC, ornithine decarboxylase).

Multiple abnormalities in the control of polyamine metabolism and uptake might be responsible for increased levels of polyamines in cancer cells as compared to that of normal cells (for review see Thomas & Thomas, 2003).

3. Biological roles in man

3.1. General

Putrescine, spermine and spermidine are flexible polycations, which exhibit under physiological conditions 2, 3 or 4 positive charges, respectively. They fulfil an array of specific roles that make them essential for growth and cell proliferation. Moreover, polyamines can interact with negatively charged structures of cells.

3.2. Participation in tumour growth

Polyamines are ubiquitous cell components with several intracellular targets including nucleic acids and membrane constituents. Their metabolism is of much interest as they are required for cell growth and proliferation. High levels of polyamines are therefore observed in rapidly divided cells and tissues such as tumour cells. Drugs interfering with polyamine biosynthesis or their biological role thus have considerable potential as therapeutic agents. Investigated chemopreventive or anti-neoplastic agents include ornithine decarboxylase inhibitors (Seiler, 2003a) and polyamine structural analogues and derivatives (Seiler, 2003b). However, tumour cells have the ability to uptake extracellular polyamines, both dietary and produced by gastrointestinal bacteria, and compensate effects of the mentioned therapeutic agents. Another approach thus started in the 1990s – deprivation of exogenous polyamines (Quemener et al., 1994). Polyamine deprivation, combining the inhibition of polyamine synthesis in tumour cells and reduction of the main exogenous sources including food and microflora-derived polyamines, has shown to be a promising therapeutic strategy. Stimulation of the anti-tumoural immune response is an additional effect of polyamine deprivation (Catros-Quemener, Chamaillard, & Bouet, 1999). However, it has not yet been experimentally proved that altering of the dietary polyamine intake can help cancer patients.

The stimulation of putrescine uptake and metabolism in enterocytes of tumour-bearing animals can be an adaptation to compensate energy deficit caused by the competition with a tumour for nutrients (Desury, Moulinoux, & Delcros, 2002). Comprehensive data on relationships between polyamine metabolism and cancer were reviewed by Catros-Quemener et al. (1999), Teti, Visalli, and McNair (2002) and Thomas and Thomas (2003).

3.3. Effects on non-neoplastic intestinal growth

As reviewed by Deloyer, Peulen, and Dandrifosse (2001), polyamines provided by food have a potential role in growth and development of the digestive system in neonatal mammals, and they also seem to be necessary for the maintenance of normal growth and general properties of the adult digestive tract. Dietary and luminal polyamines were observed to be the important local factors for growth and development of small intestinal and colonic mucosa in suckling rats (Löser, Eisel, Harms, & Folsch, 1999). In immature rats, spermidine and spermine are maturation factors that can reproduce the same increase in intestinal glycoprotein galactosylation that is normally observed during weaning (Greco et al., 2001). Maintenance of intestinal mucosal integrity requires polyamines, which regulate epithelial paracellular barrier function (Guo et al., 2003).

3.4. Other effects

Insufficient polyamine intake could play a role in the induction of sensitisation to dietary allergens as was observed both in suckling rats and in children. The probability of developing an allergy can reach 80% if the mean spermine content in milk is below 0.4 $mg\,l^{-1}$, and it is negligible if the mean spermine content is higher than 2.6 $mg\,l^{-1}$. Spermine increases proliferation and differentiation of lymphocytes isolated from childrens' tonsils (Dandrifosse et al., 2000). In an experiment with transgenic rats, insufficient hepatic pools of spermine and spermidine failed to initiate the regenerative process following partial hepatectomy (Rasanen et al., 2002). An increased intake of dietary polyamines seems to have a favourable potential for post-operation patients or during wound healing.

3.5. Toxicity

Oral acute and subacute toxicity of the individual polyamines was determined in Wistar rats. The acute toxicity was observed to be 2000, 600 and 600 $mg\,kg^{-1}$ body weight for putrescine, spermidine and spermine, respectively. The no-observed-adverse-effect level (NOAEL) was 180, 83 and 19 $mg\ kg^{-1}$ body weight for putrescine, spermidine and spermine, respectively (Til, Falke, Prinsen, & Willems, 1997). However, such extreme intakes of dietary amines cannot be supposed.

4. Absorption of polyamines from intestinal lumen

Bardócz et al. (1995) reported daily intake between 350 and 500 micromoles of polyamines in an adult from a typical British diet. Moreover, in the lumen of the upper

small bowel are also present polyamines originating from intestinal bacteria, sloughed cells and pancreatic, bile and intestinal secretions. Shortly after a meal, the majority of luminal polyamines disappear from the duodenal and jejunal lumen by a mechanism of passive diffusion. The majority of luminal polyamines are degraded in the gut before reaching systemic circulation. Polyamines are absorbed and distributed throughout the body, and then utilised for cellular growth in remote organs and tissues, including the gut, as reviewed by Milovic (2001). The most abundant polyamine in the small intestinal and colonic lumen, putrescine, is not only rapidly taken up but also rapidly converted to metabolically active spermidine and spermine.

The gastrointestinal tract can represent a significant source of polyamines in the body. In a study by Benamouzig, Mahe, Luengo, Rautureau, and Tome (1997), a considerable amount of polyamines were observed in the lumen of human gut during the fasting state, suggesting endogenous secretion. Significantly higher contents were determined in the jejunum than in the ileum, which suggests proximal absorption. Full absorption of dietary polyamines from a yoghurt test meal was also observed.

5. Content of polyamines in foods

5.1. General

Although intake of dietary polyamines has been known for years as an important factor of health and disease, data on polyamine contents in foods are limited and dispersed in the literature. Up to now, only a few papers have dealt specifically with the topic (Bardócz, Grant, Brown, Ralph, & Pusztai, 1993; Bardócz et al., 1995; Okamoto, Sugi, Koizumi, Yanadiga, & Udaka, 1997; Hernández-Jover, Izquierdo-Pulido, Veciana-Nogués, Mariné-Font, & Vidal-Carou, 1997; Eliassen, Reistad, Risøen, & Rønning, 2002). In addition, the selection of foods was rather characteristic for the respective dietary habits in Scotland, Japan, Spain and Norway. Moreover, a part of the published data was based only on 2–3 samples of the individual food items. Very limited data have been available on the effects of food processing and storage on changes in polyamine contents. Thus, nutritionists have not yet the reliable information on which to base advice.

Polyamines exist in cells in both free and conjugated forms (Bagni & Tassoni, 2001). Growth responses have been postulated to depend on the level of free polyamines, while conjugate formation is a way for regulation of cellular pool of free polyamines. In the conjugates, polyamines are bound covalently to a partner molecule (e.g., plant phenolics or membrane phospholipids) and can be released by hydrolysis with a strong acid. Even in perchloric acid extracts of plant matrices, often prepared for polyamines isolation during analytical procedures, conjugates occur in both soluble and insoluble forms. Nevertheless, most of recently accessible data do not differentiate free and conjugated polyamines in foods of plant origin. Commonly, increased spermidine and spermine levels can be supposed in metabolically highly active tissues. High putrescine contents are usually connected with high activity of several groups of bacteria, mainly *Enterobacteriaceae* and *Clostridium* spp. (for a review see Shalaby, 1996).

5.2. Polyamines in foods of plant origin

Putrescine, spermine and spermidine universally occurring in plant organs are involved in a wide array of processes, ranging from triggering organogenesis to protecting against stress. Comprehensive information on different aspects of polyamine roles in plant physiology is available in recent reviews. Mechanisms of polyamine action implicated in plant response to environmental challenges were reviewed by Bouchereau, Aziz, Larher, and Martin-Tanguy (1999), in resistance to plant pathogens by Walters (2003a, 2003b) and in the improvement of the shelf life of fruit by Valero, Martínez-Romero, and Serrano (2002). Literature data on polyamine contents in potato, vegetables, fruits, cereals, legumes and beverages are collected in Tables 1–3.

Putrescine contents are commonly the highest among polyamines. Some of the tested foods have a considerably high mean putrescine level (above 40 $mg\,kg^{-1}$), namely oranges, orange juice, mandarins, grapefruit juice and the processed foods sauerkraut, ketchup, frozen green peas and fermented soy products. Spermidine contents in plant foods are commonly higher than spermine levels. Legumes, mainly soybean, pear, cauliflower and broccoli belong to food items with the highest spermidine content, usually above 30 $mg\,kg^{-1}$. The same foods, mainly legumes, also have the highest spermine level. Moreover, the increased content of polyamines were reported by Okamoto et al. (1997) and Yen (1986) for several Chinese and Japanese fermented soy products. Wide variations of polyamine contents within the individual foods are common. Such situations can be observed in Tables 1–3 in food items with a high number of samples. Similar fluctuation of polyamine contents is characteristic also in foods of animal origin. This complicates the applicability of the literature data by dieticians.

A proportion of polyamines leaches to cooking water. For putrescine, approximately 20–25% leaches from broccoli and celery and about 40% from cauliflower and asparagus. Similarly for spermidine, 10–20% leaches from broccoli, savoy and celery, and 20–30% from cauliflower and asparagus (Ziegler et al., 1994).

Simon-Sarkadi, Holzapfel, and Halasz (1994) observed changes in polyamines during the storage of fresh

Table 1
Content of polyamines (mg kg^{-1}) in potato, vegetables and fruits

Product	n	Putrescine				Spermidine				Spermine				References
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Potato, fresh	3	9.7	–	–	–	11.2	–	–	–	3.0	–	–	–	Bardócz et al. (1993)
	3	17.6	–	–	–	13.5	–	–	–	ND	–	–	–	Okamoto et al. (1997)
	6	9.7	2.1	5.8	12.8	11.3	1.7	8.3	13.6	2.6	1.2	0.8	4.0	Eliassen et al. (2002)
Cooked	3	21.6	–	–	–	15.2	–	–	–	5.2	–	–	–	Bardócz et al. (1993)
	4	3.9	–	ND	6.9	23.5	–	13.6	35	–	–	–	–	Ziegler, Hahn, and Wallnöfer (1994)
	4	8.5	2.3	5.6	12.4	10.9	2.2	9.1	15.7	2.2	1.2	ND	3.4	Eliassen et al. (2002)
Chips	4	21.6	–	–	–	24.8	–	–	–	2.6	–	–	–	Bardócz et al. (1995)
Potato crisps	3	–	–	38.4	41.9	–	–	35.2	39.9	–	–	4.2	5.1	Bardócz et al. (1995)
Vegetables														
Cauliflower, fresh	3	–	–	3.1	4.5	–	–	21.7	27.8	–	–	2.0	2.8	Bardócz et al. (1993)
	7	4.9	–	2.2	7.6	31.2	–	17.1	42.8	–	–	–	–	Ziegler et al. (1994)
	5	5.3	2.1	3.3	8.9	28.3	6.5	21.3	39.3	6.1	1.6	4.6	8.9	Eliassen et al. (2002)
Cooked	4	4.0	1.2	2.6	5.9	26.2	10.6	19.0	45.2	6.3	2.8	4.4	11.3	Eliassen et al. (2002)
Broccoli, fresh	4	9.0	–	7.0	10.5	33.2	–	31.8	36.0	–	–	–	–	Ziegler et al. (1994)
	5	6.4	2.9	3.4	10.8	41.3	9.1	24.5	51.8	9.9	3.2	5.8	15.9	Eliassen et al. (2002)
Cooked	4	5.6	2.9	2.5	8.9	27.3	6.4	17.3	33.1	7.1	1.4	5.3	8.9	Eliassen et al. (2002)
Cabbage	3	–	–	0.4	1.6	–	–	3.2	5.1	–	–	3.2	3.6	Bardócz et al. (1993)
	4	–	–	–	–	14.4	–	13.2	16.6	–	–	–	–	Ziegler et al. (1994)
Sauerkraut	121	146	99.0	2.8	529	8.2	6.6	ND	47.0	–	–	–	–	Kalač, Špička, Křížek, Steidlová, and Pelikánová (1999)
Savoy	4	–	–	–	–	11.6	–	10.6	13.0	–	–	–	–	Ziegler et al. (1994)
Spinach, frozen purée	32	12.9	–	ND	119	7.3	3.8	1.3	15.4	2.2	1.8	ND	3.8	Kalač, Švecová, and Pelikánová (2002)
Cucumber	3	3.2	–	–		1.5	–	–	–	0.4	–	–	–	Bardócz et al. (1993)
	5	6.9	1.4	5.5	8.7	7.4	1.6	5.4	10.3	1.2	0.8	ND	2.8	Eliassen et al. (2002)
Carrot	3	–	–	1.2	1.8	–	–	7.7	8.3	–	–	2.0	2.8	Bardócz et al. (1993)
	4	2.8	–	2.0	3.9	4.5	–	4.3	4.7	–	–	–	–	Ziegler et al. (1994)
	2	3.5	–	–	–	8.0	–	–	–	ND	–	–	–	Okamoto et al. (1997)
	6	1.5	0.7	0.7	2.7	6.7	2.3	3.6	11.9	0.6	1.2	ND	3.8	Eliassen et al. (2002)
Tomato	3	–	–	9.3	122	–	–	1.6	2.5	ND	–	–	–	Bardócz et al. (1993)
	2	10.6	–	–	–	1.7	–	–	–	ND	–	–	–	Okamoto et al. (1997)
Concentrated tomato pasta	19	25.9	8.2	7.9	41.1	8.4	3.7	ND	15.8	–	–	ND	2.9	Kalač et al. (2002)
Ketchup	24	52.5	54.1	ND	165	6.1	9.0	ND	33.4	–	–	ND	12.1	Kalač et al. (2002)
Onion	3	–	–	5.5	7.2	–	–	5.5	8.1	–	–	0.8	1.2	Bardócz et al. (1993)
Lettuce	3	–	–	3.3	4.8	–	–	4.2	8.3	ND	–	–	–	Bardócz et al. (1993)
	3	5.6	1.3	4.5	7.3	9.1	1.5	7.4	10.3	0.8	0.8	ND	1.8	Eliassen et al. (2002)
Celeriac	3	6.1	–	3.7	7.7	26.7	–	19.7	34.7	–	–	–	–	Ziegler et al. (1994)
Asparagus	3	2.9	–	2.0	3.8	10.3	–	9.2	10.9	–	–	–	–	Ziegler et al. (1994)
Fruits														
Apple	3	–	–	0.4	1.7	–	–	2.2	2.8	ND	–	–	–	Bardócz et al. (1993)
	2	ND	–	–	–	1.0	–	–	–	ND	–	–	–	Okamoto et al. (1997)
Pears	3	–	–	23.6	24.2	–	–	30.2	76.0	–	–	8.1	49.3	Bardócz et al. (1993)
Orange	3	–	–	95.1	140	–	–	8.8	9.7	ND	–	–	–	Bardócz et al. (1993)
	2	117	–	–	–	1.9	–	–	–	1.6	–	–	–	Okamoto et al. (1997)
	5	137	11.3	119	153	4.1	4.0	0.4	11.6	0.2	0.2	ND	1.4	Eliassen et al. (2002)
Orange, canned	3	–	–	27.0	30.0	–	–	0.7	1.0	ND	–	–	–	Bardócz et al. (1993)
Mandarin	10	122	44.2	67.3	200	2.3	1.3	ND	4.5	0.4	0.8	ND	3.0	Eliassen et al. (2002)

n, number of samples; x, mean value; S_x, standard deviation; ND, content below detection limit.

Chinese cabbage, endive, iceberg lettuce and radicchio at 5 °C over five days. Only the putrescine content increased 3–8-fold during this period, while spermidine and spermine levels did not change significantly.

An investigation of polyamine content changes during the ageing of red wine variety Merlot over 250 days showed an increase of putrescine content from 9 to 16 mg l^{-1} and a steady level of spermine 1.4 mg l^{-1}. No

Table 2
Content of polyamines (mg kg^{-1}) in cereals and legumes

Product	n	Putrescine				Spermidine				Spermine				References
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Cereals														
Wheat flour	2	1.5	–	–	–	9.6	–	–	–	5.3	–	–	–	Okamoto et al. (1997)
Bread, white	3	–	–	1.5	1.8	–	–	5.0	5.2	–	–	3.4	3.8	Bardócz et al. (1993)
Whole grain	3	–	–	0.5	0.9	–	–	21.3	27.4	–	–	7.1	9.1	Bardócz et al. (1993)
	5	3.4	0.5	2.5	4.0	13.1	1.5	10.2	14.8	6.3	2.0	3.4	8.7	Eliassen et al. (2002)
Pasta, cooked	3	–	–	1.0	1.1	–	–	7.0	7.3	–	–	10.5	12.9	Bardócz et al. (1993)
Breakfast cereals, mixed	10	–	–	2.0	2.2	–	–	24.1	24.4	–	–	6.1	6.7	Bardócz et al. (1995)
Rice, polished	2	<0.9	–	–	–	3.9	–	–	–	<4.1	–	–	–	Okamoto et al. (1997)
Cooked	3	–	–	1.0	1.3	–	–	1.3	1.6	–	–	8.1	10.1	Bardócz et al. (1993)
Legumes														
Green peas, frozen	14	46.3	27.0	11.7	107	46.6	23.5	2.9	88.4	3.8	2.0	ND	8.5	Kalač et al. (2002)
Cooked	3	–	–	5.4	5.9	–	–	62.1	68.2	–	–	33.5	71.7	Bardócz et al. (1993)
Green beans, cooked	3	–	–	4.3	5.4	–	–	7.7	8.8	–	–	4.6	5.5	Bardócz et al. (1993)
Red kidney bean	3	–	–	0.3	0.4	–	–	19.0	20.0	–	–	22.8	25.7	Bardócz et al. (1993)
Soybean, dried	3	–	–	1.6	6.5	–	–	33.2	62.1	–	–	29.7	34.3	Bardócz et al. (1993)
	1	17.0	–	–	–	128	–	–	–	–	–	–	–	Ziegler et al. (1994)
	2	41	–	–	–	207	–	–	–	69	–	–	–	Okamoto et al. (1997)
Soybean miso	11	51.1	40.7	9.8	143.1	–	–	–	–	–	–	–	–	Yen (1986)
	2	20.2	–	–	–	11.7	–	–	–	2.0	–	–	–	Okamoto et al. (1997)
Soy sauce	22	88.1	129	ND	514	–	–	–	–	–	–	–	–	Yen (1986)
Koikuchi	2	47.5	–	–	–	14.5	–	–	–	<1.0	–	–	–	Okamoto et al. (1997)
Different	23	–	–	ND	205	–	–	–	–	–	–	–	–	Stute, Petridis, Steinhart, and Biernoth (2002)

Table 3
Content of polyamines (mg l^{-1} or mg kg^{-1}) in beverages

Product	n	Putrescine				Spermidine				Spermine				References
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Beer	Hundreds	~4	–	<0.3	30.7	~0.7	–	ND	6.8	~0.3	–	ND	3.9	Kalač and Křížek (2003)
Wine, red	8	11.6	14.7	1.9	49.0	0.7	0.4	ND	1.3	ND	–	–	–	Eliassen et al. (2002)
Red	6	9.6	5.6	–	–	ND	–	–	–	0.16	0.25	–	–	Romero, Sánchez-Viñas, Gázquez, and Bagur (2002)
Rosé	7	6.0	3.0	–	–	0.1	0.0	–	–	ND	–	–	–	Romero et al. (2002)
White	6	4.3	4.2	–	–	ND	–	–	–	ND	–	–	–	Romero et al. (2002)
Grapefruit juice	3	98.6	–	–	–	ND	–	–	–	ND	–	–	–	Bardócz et al. (1993)
Orange juice, w/pulp	3	85.0	11.4	76.6	100	2.5	0.9	1.9	3.8	ND	–	–	–	Eliassen et al. (2002)
Preserved	3	54.6	2.6	51.3	57.4	1.9	0.15	1.7	2.0	ND	–	–	–	Eliassen et al. (2002)
Tea, black leaves	3	–	–	14.4	16.1	–	–	36.5	39.7	–	–	57.8	60.0	Bardócz et al. (1995)
Infusion	3	ND	–	–	–	0.2	–	–	–	ND	–	–	–	Bardócz et al. (1995)
Black leaves	2	7.0	–	–	–	11.4	–	–	–	19.0	–	–	–	Okamoto et al. (1997)
Oolong leaves	2	–	–	8.8	30.8	–	–	20.3	47.9	11.7	–	–	–	Okamoto et al. (1997)
Coffee, green	?	10.3	1.0	9.1	16.3	6.0	0.7	5.1	6.8	4.4	0.8	4.2	7.3	Cirilo et al. (2003)
Granules	3	–	–	2.9	3.3	–	–	2.6	3.5	–	–	0.2	0.6	Bardócz et al. (1995)
Infusion	3	0.1	–	–	–	ND	–	–	–	ND	–	–	–	Bardócz et al. (1995)

differences were observed between ageing in barrels from American oak or French oak (Moreno, Goñi, & Azpilicueta, 2003).

During the roasting of green coffee, the complete loss of putrescine and spermine was observed and a considerable decrease of spermidine content. Spermidine losses were higher under conditions of American roasting for 6 min as compared with French roasting for 12 min (Cirilo et al., 2003).

Irradiation of Korean soybean paste prior to fermentation suppressed significantly the formation of putrescine and supported the decrease of spermidine content, while spermine levels were unaffected as compared to an untreated control (Kim et al., 2003).

5.3. Polyamines in meat, fish and meat products

Literature data on polyamine contents in beef, pork and chicken meat and meat products and in fish are given in Table 4. In contrast to foods of plant origin, low levels of putrescine are typical for well-treated foods of animal origin. Fish sauces, cod roe and canned crab are the reported exceptions. High spermine contents, usually between 20 and 60 mg kg^{-1}, are usual in meat and meat products of warm-blooded animals. Lower spermine contents, commonly below 10 mg kg^{-1}, were reported in fish. Spermidine levels in meat and fish rarely exceed 10 mg kg^{-1}. Thus, an opposite relation between spermidine and spermine contents is typical for foods of animal origin as compared with plant products. Silva and Glória (2002) explain higher spermidine than spermine contents in their samples of chicken-based meat products (see Table 4) by the incorporation of a considerable proportion of vegetable components.

The literature information on changes of polyamine contents during meat storage is not unequivocal. Edwards, Dainty, and Hibbard (1983) observed an increase of putrescine contents in intact beef, pork and lamb and in minced beef stored at 5 °C, consistent with the total count of viable aerobic bacteria. Contents of putrescine, spermidine and spermine increased significantly, somewhat increased and remained stable, respectively, in minced meat of non-specified origin incubated for seven days at 20–22 °C. Addition of glucono-delta-lactone suppressed significantly the formation of putrescine (Maijala, Eerola, Aho, & Hirn, 1993). Similar results were reported by Yano et al. (1995), who observed a considerable increase of putrescine content over 13 days of storage, while no changes in spermidine and spermine contents during storage up to 39 days in vacuum-packed beef sirloin at 0, 5 or 10 °C. Vinci and Antonelli (2002) also reported an increase of putrescine levels in beef and chicken meat stored at 4 °C for 36 days, while spermine content decreased in both beef and chicken meat. Initially a low spermidine content increased in beef but decreased in chicken meat. In minced and sliced pork meat stored at 6–8 °C for eight days the putrescine content increased quickly and significantly, spermidine content remained stable and spermine content decreased gradually (Hernández-Jover, Izquierdo-Pulido, Veciana-Nogués, Mariné-Font, & Vidal-Carou, 1996).

Suzzi and Gardini (2003) reviewed numerous articles dealing with the effects of multiple factors on the formation of biogenic amines in dry fermented sausages. Contents of putrescine, spermidine and spermine in this very variable group of meat products are usually in tens or hundreds, ones and tens of mg kg^{-1}, respectively. The most important change, as compared to meat, is a very high level of putrescine. In a classical work, Mietz and Karmas (1978) included polyamines as indicators of seafood decomposition. They observed that spermidine and spermine contents decreased during storage, while putrescine content increased. In recent years, similar changes were observed in Mediterranean hake. Putrescine content increased significantly during storage for 29 days, being more intensive at 6–8 °C than at 0 °C (in ice). Spermidine and spermine contents somewhat decreased from the initial levels 4 and 10 mg kg^{-1}, respectively (Baixas-Nogueras, Bover-Cid, Veciana-Nogués, & Vidal-Carou, 2002). Similarly, an extensive formation of putrescine and a slight decrease of spermidine content were determined in carp meat, while spermine content remained stable during storage at 3 or 15 °C until spoilage (Křížek, Pavlíček, & Vácha, 2002).

Veciana-Nogués et al. (1997b) reported a significant decrease of spermidine and spermine content during the canning process of tuna, while putrescine level remained stable. The same laboratory (Veciana-Nogués, Bover-Cid, Mariné-Font, & Vidal-Carou, 2004) observed insignificant changes of spermidine and spermine contents in tuna fish inoculated with *Morganella morganii* and *Klebsiella oxytoca* as compared with an aseptic control. The variants were stored in ice, under refrigeration and at room temperature. The potential ability of *M. morganii* to form putrescine was not shown in the inoculated samples, regardless of the storage temperature.

Putrescine and spermidine contents increased considerably to about 20 mg kg^{-1} during the initial stage of fresh nobbed sardines maturation and the matured fish were stable at 22–24 °C until day 240 of storage. Changes of both polyamines were limited during maturation of fresh gutted and of both frozen nobbed and gutted fish (Mendes, Gonçalves, & Nunes, 1999). Anchovy immersed in oil is a semi-preserved fish product prepared without heating. Putrescine content was stable during anchovy storage at 8–10 °C or at 20 ± 1 °C for nine months, whereas spermidine and spermine contents changed differently in three different tested commercial brands (Veciana-Nogués et al., 1997a). Nevertheless, the changes seem to be unimportant from the nutritional point of view.

Table 4
Content of polyamines (mg kg^{-1}) in beef, pork and chicken meat, meat products and in fish and fish products

Product	n	Putrescine				Spermidine				Spermine				Reference
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Beef														
Raw, lean	3	–	–	5.5	5.9	–	–	18.3	19.7	–	–	30.7	42.0	Bardócz et al. (1993)
	2	0.5	–	–	–	2.6	–	–	–	28.3	–	–	–	Okamoto et al. (1997)
	6	–	–	–	–	3.1	0.8	1.9	4.2	39.8	5.8	28.7	44.6	Hernández-Jover et al. (1997)
	5	10.1	14.3	0.8	38.5	5.5	3.2	2.6	12.0	27.3	4.4	16.8	26.0	Eliassen et al. (2002)
Ground	3	8.8	–	–	–	–	–	70.6	72.9	–	–	46.3	47.5	Bardócz et al. (1993)
	8	4.0	5.7	0.8	18.7	3.0	0.7	2.2	4.8	20.8	3.6	13.3	26.7	Eliassen et al. (2002)
Cooked	3	–	–	1.9	2.8	–	–	5.7	6.8	–	–	22.8	33.3	Bardócz et al. (1993)
Fried	2	–	–	1.4	30.2	–	–	2.6	5.7	–	–	26.1	36.2	Eliassen et al. (2002)
Sirloin, raw	6	–	–	–	–	1.5	–	–	–	30	–	–	–	Yano, Kataho, Watanabe, Nakamura, and Asano (1995)
	7	2.1	3.2	0.6	12.8	2.2	0.6	1.0	3.0	17.0	6.7	6.1	29.1	Eliassen et al. (2002)
Pork														
Raw, lean	3	3.1	–	–	–	–	–	2.9	4.9	–	–	30.1	70.3	Bardócz et al. (1993)
	2	1.1	–	–	–	4.6	–	–	–	28.3	–	–	–	Okamoto et al. (1997)
	13	–	–	–	–	3.0	1.0	0.8	4.5	33.5	4.4	27.3	40.6	Hernández-Jover et al. (1997)
Chops, raw	5	0.2	0.3	ND	0.7	2.8	0.7	2.0	4.1	22.4	7.5	14.5	34.5	Eliassen et al. (2002)
Meat products														
Sausage	3	–	–	13.8	14.5	–	–	5.8	6.4	–	–	24.0	25.9	Bardócz et al. (1993)
Sausage, wiener	5	0.9	0.3	0.4	1.1	2.3	0.7	1.2	3.5	9.9	2.0	5.0	12.5	Eliassen et al. (2002)
Mortadella (cooked salami)	20	–	–	ND	5.7	4.0	2.3	1.0	8.9	17.2	7.5	7.6	32.2	Hernández-Jover et al. (1997)
Pork ham, smoked	3	–	–	4.0	4.3	–	–	2.0	8.8	–	–	40.2	50.3	Bardócz et al. (1993)
Roasted	3	9.0	–	–	–	6.1	–	–	–	–	–	40.2	60.4	Bardócz et al. (1993)
Cooked	20	–	–	ND	12.4	2.1	0.6	1.4	3.5	21.4	8.4	6.4	35.7	Hernández-Jover et al. (1997)
Dry-cured	23	–	–	ND	17.4	5.6	0.9	4.4	7.3	35.7	8.2	24.9	62.1	Hernández-Jover et al. (1997)
Ripened dry fermented Spanish sausage "chorizo"	20	–	–	2.6	416	4.1	2.5	1.9	10.0	26.1	8.1	13.8	43.5	Hernández-Jover et al. (1997)
	3	–	–	0.8	185	–	–	6.7	8.2	–	–	39.1	58.8	Ruiz-Capillas and Jiménez-Colmenero (2004)
Different Spanish meat products	17	–	–	0.2	10	–	–	1.7	7.6	–	–	17.8	59.3	Ruiz-Capillas and Jiménez-Colmenero (2004)
Game (stored at 4 °C for 7 days)														
Roe deer	3	19.3	17.4	–	–	14.7	2.9	–	–	54.3	7.4	–	–	Dičáková et al. (2003)
Red deer	3	9.0	7.6	–	–	17.0	7.0	–	–	59.3	2.3	–	–	Dičáková et al. (2003)
Fallow deer	3	38.0	17.8	–	–	14.7	2.7	–	–	60.7	0.7	–	–	Dičáková et al. (2003)
Pheasant	3	ND	–	–	–	21.0	1.0	–	–	83.0	6.9	–	–	Dičáková et al. (2003)
Chicken														
Raw	3	2.9	–	–	–	9.3	–	–	–	59.2	–	–	–	Bardócz et al. (1993)
	2	<0.4	–	–	–	2.9	–	–	–	62.6	–	–	–	Okamoto et al. (1997)
Grilled	5	2.0	0.5	1.3	2.7	17.3	3.9	13.2	25.7	44.4	6.1	33.7	53.1	Eliassen et al. (2002)
Chicken breast, raw	4	<0.8	–	–	–	7.3	0.8	–	–	17.9	1.3	–	–	Silva and Glória (2002)
Chicken thigh, raw	4	<0.8	–	–	–	7.2	1.8	–	–	16.2	0.9	–	–	Silva and Glória (2002)
Chicken based frankfurter	10	0.6	–	ND	1.4	15.8	–	11.9	26.6	10.8	–	6.0	17.1	Silva and Glória (2002)
Mortadella	10	2.6	–	ND	19.2	10.8	–	4.9	24.3	10.1	–	6.4	15.9	Silva and Glória (2002)
Hamburger	10	0.6	–	ND	1.9	12.6	–	4.2	24.4	9.2	–	4.5	15.6	Silva and Glória (2002)

Table 4 (*continued*)

Product	*n*	Putrescine				Spermidine				Spermine				Reference
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Various poultry meat based products	51	–	–	ND	6.2	–	–	ND	8.9	–	–	–	–	Dičáková, Sokol, Cabadaj, and Bystrický (1999)
Fish														
Cod, raw	3	–	–	26.4	29.7	–	–	1.0	1.6	–	–	3.0	6.5	Bardócz et al. (1993)
	9	1.4	0.9	0.5	3.1	0.6	0.9	ND	3.8	0.6	0.8	ND	2.2	Eliassen et al. (2002)
Salted	5	4.9	3.0	2.1	9.6	1.5	1.0	ND	2.5	2.6	1.6	ND	3.8	Eliassen et al. (2002)
Cod roe	6	90.9	17.8	79.3	129	13.6	4.2	7.8	18.8	20.0	6.5	9.9	26.9	Eliassen et al. (2002)
Salmon, raw	9	2.7	1.0	1.6	4.6	1.5	0.7	0.4	3.3	0.8	0.8	ND	3.2	Eliassen et al. (2002)
Mackerel, raw	7	2.4	0.7	1.3	3.5	2.9	0.9	1.6	4.1	3.0	2.4	ND	7.7	Eliassen et al. (2002)
In tomato, canned	5	7.4	2.1	3.9	9.7	3.0	1.2	1.4	4.4	1.4	1.4	ND	4.2	Eliassen et al. (2002)
Tuna, fresh	20	–	–	ND	4.8	–	–	1.2	11.7	–	–	7.3	37.0	Veciana-Nogués, Mariné-Font, and Vidal-Carou (1997b)
Canned	38	–	–	ND	2.2	–	–	1.5	10.0	–	–	2.2	35.2	Veciana-Nogués et al. (1997b)
	10	5.6	7.1	1.3	25.4	5.4	1.6	1.9	8.0	7.9	1.6	5.3	10.3	Eliassen et al. (2002)
Anchovies, immersed in oil	3	5.0	–	2.3	7.6	2.2	–	2.1	2.3	7.7	–	7.5	7.9	Veciana-Nogués, Mariné-Font, and Vidal-Carou (1997a)
Crab, canned	2	–	–	110	134	–	–	1.2	1.5	–	–	2.0	2.2	Eliassen et al. (2002)
Trout	3	–	–	1.8	1.9	–	–	3.9	4.2	–	–	8.7	9.1	Bardócz et al. (1993)
Fish sauces ($mg\,kg^{-1}$ dry matter)	45	–	–	ND	1260	–	–	–	–	–	–	–	–	Stute et al. (2002)

5.4. Polyamines in milk and milk products, human breast milk and eggs

Polyamine contents in further foods of animal origin and in human milk are given in Table 5. Levels of all polyamines are very low in cow milk, yoghurt, human milk and hen eggs. However, contents of all polyamines can reach an extremely high level in cheeses, mainly in matured types. Motyl et al. (1995) observed large multifactorial variations in cow milk spermidine and spermine contents: cow to cow, lactation phase related, and milk yield dependent variability. The highest contents of both amines were in colostrum. Contents of both spermidine and spermine increased during the lactic acid fermentation of milk inoculated with *Lactococcus lactis* starter cultures. The addition of rennet promoted spermidine and putrescine formation, while the addition of $0.5\ g\,l^{-1}$ common salt slowed the rate of formation of both all polyamines and biogenic amines. Temperature should be below 20 °C during the process (Santos et al., 2003).

In a survey of 100 samples of a non-matured cheese and four types of matured Spanish cheeses (Table 5), Novella-Rodríguez et al. (2003) found out that polyamine contents decreased in order putrescine $\gg$ spermidine $>$ spermine, varying among different types of ripened cheeses and also within the same type of cheese. In a study trying to identify conditions of cheese-making that minimised contents of the four main biogenic amines, including putrescine, the effects of three factors were tested: using raw or pasteurised milk, thermophilic or mesophilic starter bacteria and unheated or heated curd. The best conditions seemed to be the use of pasteurised milk, mesophilic starters and heated curd (Genaro, Gianotti, Marengo, Pattono, & Turi, 2003). However, optimum conditions were different for the individual amines and spermidine and spermine contents were not determined.

Novella-Rodríguez, Veciana-Nogués, Trujillo-Mesa, and Vidal-Carou (2002) compared the effects of high-pressure treatment and of pasteurisation of goat milk on formation of biogenic amines and polyamines in cheese during 45 days of maturation. Pressure treatment can cause higher proteolysis than pasteurisation, leading to a higher release of free amino acids as the precursors the amine formation. The effect of pressure treatment proved to be minimal, differences between the amine contents in the both variants were low.

The literature dealing with polyamine contents in human milk was reviewed by Löser (2000). Content of polyamines varies during the suckling period. During the first week postpartum, putrescine levels remained very low, while spermidine and spermine contents rose markedly during the initial three days, reaching plateau

Table 5
Content of polyamines (mg l^{-1} or mg kg^{-1}) in milk, milk products, human breast milk and eggs

Product	n	Putrescine				Spermidine				Spermine				References
		x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	x	S_x	x_{min}	x_{max}	
Cow milk														
Full cream	3	0.09	–	–	–	–	–	0.15	0.45	–	–	0.2	0.6	Bardócz et al. (1993)
Semi-skimmed	3	–	–	0.09	0.18	–	–	0.3	0.6	–	–	0.2	0.4	Bardócz et al. (1993)
Full cream	5	–	–	–	–	–	–	0.25	0.85	–	–	0.4	1.6	Motyl, Płoszaj, Wojtasik, Kukulska, and Podgurniak (1995)
Unspecified	5	ND	–	–	–	0.17	–	0.16	0.18	ND	–	–	–	Novella-Rodríguez, Veciana-Nogués, and Vidal-Carou (2000)
Reconstituted powdered	4	–	–	–	–	0.75	–	–	–	0.2	–	–	–	Santos, Souza, Cerqueira, and Glória (2003)
Yoghurt,plain														
	5	ND	–	–	–	–	–	ND	0.43	–	–	ND	0.34	Novella-Rodríguez et al. (2000)
	5	0.3	0.4	0	0.9	0.7	0.6	0	1.3	0.8	1.0	0	2.2	Eliassen et al. (2002)
Cheeses														
Cheddar, fresh	3	–	–	10.1	20.0	–	–	80.8	109	–	–	23.8	39.2	Bardócz et al. (1993)
Cheddar, matured	3	653	–	–	–	–	–	197	202	–	–	23.2	40.0	Bardócz et al. (1993)
Camembert	2	ND	–	–	–	<1.5	–	–	–	ND	–	–	–	Okamoto et al. (1997)
Gouda	2	ND	–	–	–	ND	–	–	–	ND	–	–	–	Okamoto et al. (1997)
Blue, Japanese	2	6.7	–	–	–	20.3	–	–	–	ND	–	–	–	Okamoto et al. (1997)
Blue, Norwegian	3	16.4	2.7	12.6	20.2	23.8	4.1	20.2	29.3	0.4	0.8	0	2.0	Eliassen et al. (2002)
Unripened, Spanish	10	–	–	ND	1.4	–	–	0.39	0.82	–	–	ND	1.12	Novella-Rodríguez et al. (2000)
Ripened, Spanish	10	–	–	ND	612	–	–	ND	43.0	–	–	ND	18.7	Novella-Rodríguez et al. (2000)
Unripened, Spanish	20	–	–	ND	3.1	–	–	ND	0.8	–	–	ND	1.1	Novella-Rodríguez, Veciana-Nogués, Izquierdo-Pulido, and Vidal-Carou (2003)
Hard-ripened from raw milk, Spanish	20	–	–	ND	670	–	–	ND	39.6	–	–	ND	21.5	Novella-Rodríguez et al. (2003)
Hard-ripened from pasteurised milk, Spanish	20	–	–	ND	612	–	–	ND	43.0	–	–	ND	18.7	Novella-Rodríguez et al. (2003)
Blue, Spanish	20	–	–	3.0	257	–	–	ND	71.6	–	–	ND	18.9	Novella-Rodríguez et al. (2003)
Goat, Spanish	20	–	–	ND	192	–	–	ND	14.5	–	–	ND	3.6	Novella-Rodríguez et al. (2003)
Human breast milk														
		0.02	–	–	–	0.32	0.09	–	–	0.63	0.03	–	–	Buts, De Keyser, De Deraemaeker, Collette, and Sokal (1995)
Eggs, boiled														
	3	–	–	0.26	0.35	–	–	0	0.15	–	–	0.2	0.6	Bardócz et al. (1995)
	2	<0.4	–	–	–	<1.4	–	–	–	<1.1	–	–	–	Okamoto et al. (1997)

levels that were 12 and 8 times higher, respectively, than the values determined on the initial day of lactation. The mean values are given in Table 5 (Buts et al., 1995). After four months of lactation, putrescine content slightly increased, whereas spermine and spermidine contents remained almost stable (Romain, Dandrifosse, Jeusette, & Forget, 1992). Mothers seem consistently to have relatively high or relatively low contents of spermidine and spermine in their milk. These individual variations may be due to diet, lifestyle or genetic background (Dandrifosse et al., 2000). Spermidine and spermine contents in infant powdered formulas were observed to be consid-

erably lower than values usual in breast milk (Buts et al., 1995; Romain et al., 1992). Polyamine contents in boiled eggs were found to be very low, however, only values of five samples were reported (Table 5).

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