Thermal Processing Contaminants in Foodstuffs and Potential Strategies of Control

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Abstract: Over the past decades, researchers from academia, industry, and National authorities and enforcement laboratories, have gained increasing insight in understanding the presence, formation and potential risk to public health posed by the compounds formed during the domestic cooking and heat-processing of different foods. Compounds already intensively studied are the heterocyclic aromatic amines, polycyclic aromatic hydrocarbons, and chloropropanols. Concrete measures have been introduced by the food industry to control certain contaminants, exemplified by the introduction of enzymatic hydrolysis of plant proteins or over-neutralization to reduce concentrations of chloropropanols in savoury flavours. The recent discovery of acrylamide in cooked foods has raised much concern, and sparked intensive scientific studies into the occurrence, analysis, exposure, mechanisms of formation, possible measures of control, and toxicology of the compound. However, since acrylamide formation is directly linked to the desired Maillard reaction that generates important flavour and aroma compounds – as well as chemicals with potentially beneficial health effects – any measures taken must assess the impact on overall quality and consumer acceptance of the food product. In addition, mitigation must be devised in such a way as not to increase the risks for other possibly more severe short and medium to long-term health risks. In this context, understanding the impact of changes in processing on the safety of foods will be of paramount importance. In May 2004 the US FDA published findings of trace levels of furan in different foods, corroborating older data and raising some concerns, albeit without reference to any health risks. Particularly canned and jarred foods that are subject to thermal treatment are apparently affected, as the volatile furan is essentially "trapped" in the food container. Analogous to the acrylamide concern, there is a paucity of knowledge in all scientific domains, i.e. exposure, methods of analysis, mechanisms of formation, toxicology. Finally, a concern that needs to be addressed is the lack of knowledge about the effects of final preparation in food service and domestic situations on the formation of processing contaminants. In essence, consumers should follow sound dietary and health advice by choosing diets based on balance, variety and moderation.

Keywords: processing contaminant; Maillard reaction products; acrylamide; 3-MCPD; furan

INTRODUCTION

The thermal processing of foods, domestically or industrially, is an ancient practice that improves the organoleptic properties of the foods, their preservation, and microbiological safety. Heat induces chemical change and a plethora of new molecules are generated in foods, some of which have been claimed to impart positive health effects, e.g. acting as antioxidants and antimutagens. On the other hand, certain compounds may be formed that exhibit carcinogenic and in some cases mutagenic properties, such as the heterocyclic aromatic amines (HAA's) [1], polycyclic aromatic hydrocarbons (PAH's) [2], and chloropropanols (e.g. 3-monochloropropanediol, 3-MCPD) [3]. In particular the HAA's and PAH's are classes of compounds that are formed under severe thermal conditions, and sources of the latter may also be occupational environment, tobacco smoke, and air pollution.

Recently, much concern was raised after the discovery of acrylamide in certain cooked foods [4], and its formation was linked to the Maillard reaction and in particular the amino acid asparagine [5–7]. Other compounds are formed in the late-stage of the Maillard reaction. These late products and cross-links formed from glycated proteins are collectively termed advanced glycation end products (AGE's), and common examples are $^{\epsilon}N$-carboxymethyl lysine (CML), pentosidine, and pyrraline. The importance of dietary AGEs and associated potential health risks are still under study [8]. However, in many cases the detailed mechanism(s) of formation of heat-induced toxicants in foods are poorly understood, as exemplified by the recent discovery of furan in certain cooked foods [9].

As a consequence of the recent discovery of the widespread occurrence of acrylamide in cooked foods, several research projects at international level have been launched to better understand the formation, potential control, and health risks of thermally generated compounds in our everyday diets. All stakeholders, i.e. the food industry, academia, private and government research institutes, regulatory authorities, have acknowledged the research gaps in this wide and complex field.

Figure 1 depicts an overview of the principle food product groups (standard diets) and the potentially "undesired" compounds that may be procured due to essentially thermal treatment (source: ICARE presentation from June 2004, a European collective research).

This report summarizes the progress made to date in understanding the fundamental mechanistic aspects of the formation of processing contaminants, focusing in particular on acrylamide and chloropropanols (3-MCPD). The feasibility of devising measures to potentially reduce (on a relative scale) the exposure of consumers to these compounds is also addressed.

CHLOROPROPANOLS

Background and occurrence in food

Chloropropanols are food-borne contaminants that may be formed in a wide variety of industrially and domestically produced foods and food ingredients. Their occurrence was first reported in acid-hydrolyzed vegetable proteins (HVP) [3], and 3-monochloropropanediol (3-MCPD) is the most commonly occurring member of the group. 3-MCPD has also been found in foods prepared without acid-hydrolysis, such as grilled cheese or roasted cereals, notably barley during the production of malt or toasted bread [10]. The UK Food Standards Agency has conducted several surveys on 3-MCPD (and dichloropropanol, DCP)
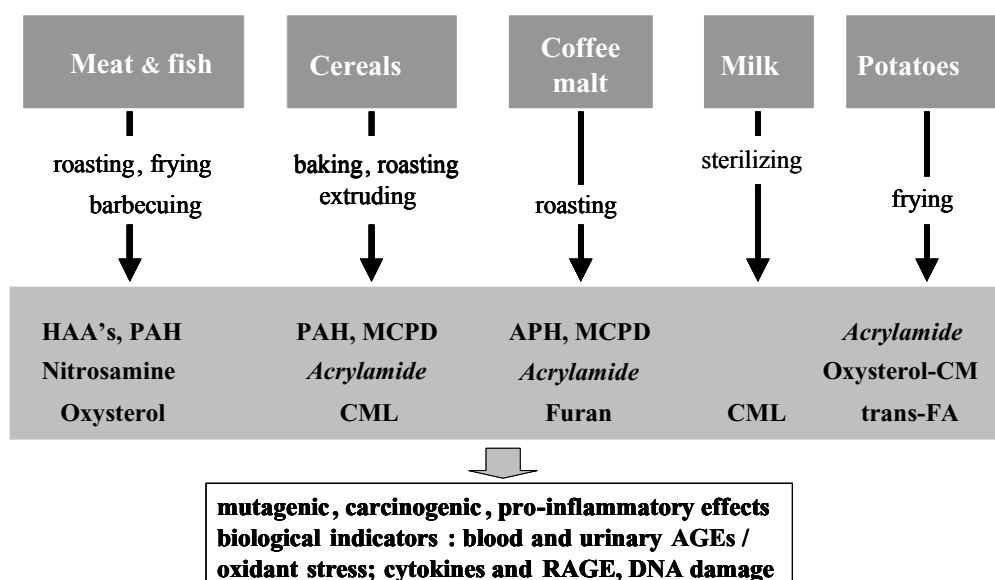
Figure 1. Formation of undesired heat-related compounds during domestic or industrial cooking (source: ICARE presentation 6/2004)

in different foods [11]. The focus of these surveys was soy sauces and related products, as well as a broader category of other foods. The latter food group has identified bread and biscuits (toasted or roasted), cooked/cured fish or meat, as most likely to harbour 3-MCPD.

3-MCPD is considered to be a non-genotoxic carcinogen working through a threshold mechanism. Therefore a tolerable intake level was derived by FAO/WHO JECFA [12] and the EU SCF [13]. Both scientific expert committees have independently established a tolerable daily intake for 3-MCPD of 2 µg/kg body weight/day. 3-MCPD is regulated within the EU and Commission Regulation (EC) No. 466/2001 sets limits for 3-MCPD in soy sauce and hydrolyzed vegetable protein (HVP) at 0.02 mg/kg based on the liquid product containing 40% dry matter.

Mechanisms of formation

Several mechanisms of formation and potential precursors of chloropropanols in foods have been proposed and discussed [14]. Heat-induced reactions leading to the formation of chloropropanols include reactions of hydrochloric acid with glycerol, lipids and carbohydrates. All reactions require prolonged heating temperatures above 100°C [15]. The key step involves the nucleophilic substitution of the acyl group by the chloride anion at positions activated by neighbouring ester groups. The resulting intermediate is a chloropropanediol di-ester that under hydrolytic conditions leads to the formation of chloropropanol. A full review on the occurrence and the mechanisms governing the formation of 3-MCPD has recently been presented by Hamlet *et al.* [14].

However, not all chemical mechanisms necessitate triglycerides. An alternative route involving allyl alcohol (prop-2-en-1-ol) has been described, that in the presence of hypochlorous acid (HOCl) may lead to the formation of chloropropanols [14]. This reaction may be important in heat-treated garlic and onions, which harbour the precursor of allyl alcohol, namely the cysteine amino acid alliin [(*S*)-allyl-L-cysteine sulphoxide].

Surveys on the occurrence of chloropropanols have revealed that 3-MCPD is found in several foodstuffs that are fermented and/or not subjected to thermal treatment, such as meats (ham, salami), fish, and fermented cheese [16]. The hitherto unexplained sources of traces of 3-MCPD in many of these foods led us to conduct fundamental model studies to assess the possible involvement of hydrolytic enzymes in the formation of chloropropanols. This study revealed for the first time an alternative pathway to the formation of these processing contaminants at relatively low temperatures, induced by lipase in the presence of oils, water, and sodium chloride [17].

It is proposed that the hydrolysis of fatty acids originating from triacylglycerols by the action of lipase occurs in different catalytic steps. First, a non-covalent Michaelis complex involving the enzyme and the substrate is formed. Then, the attack of the nucleophilic serine O^γ will generate a tetrahedral, hemiacetal intermediate, the oxyanion being stabilized by two or three hydrogen bonds (the so-called oxyanion hole). Subsequently, the substrate ester bond is cleaved and the tetrahedral intermediate broken down to the acyl-enzyme. Finally, the acyl-enzyme is cleaved, the leaving group protonated and the fatty acid dissociated (Figure 2).

This study has also revealed that enzyme catalyzed formation of 3-MCPD depends on the activity and specificity of the lipase, the pH, Cl^-, temperature, and the water activity of the food system. Technical lipases and lipases from ingredients have a preference for the hydrolysis of short-medium chain and saturated fatty acids. Lipase activities found in ingredients and soups correlate well with 3-MCPD formation observed during storage of culinary dried products [17]. As far as the mechanistic aspects are concerned, more detailed work especially in identifying the chlorinated acyl intermediates and their role as possible substrates of hydrolytic enzymes is warranted.

Potential strategies of control

After the initial discovery of chloropropanols as a contaminant in savoury foods containing acid HVP, the industrial process was radically changed and could achieve a significant reduction of 3-MCPD concentrations by a factor of more than 1000-fold. The following main production parameter changes were introduced:

(*i*) Change from acid hydrolysis to an enzymatic process

(*ii*) Employment of the over-neutralization technique by adding NaOH after acid hydrolysis.
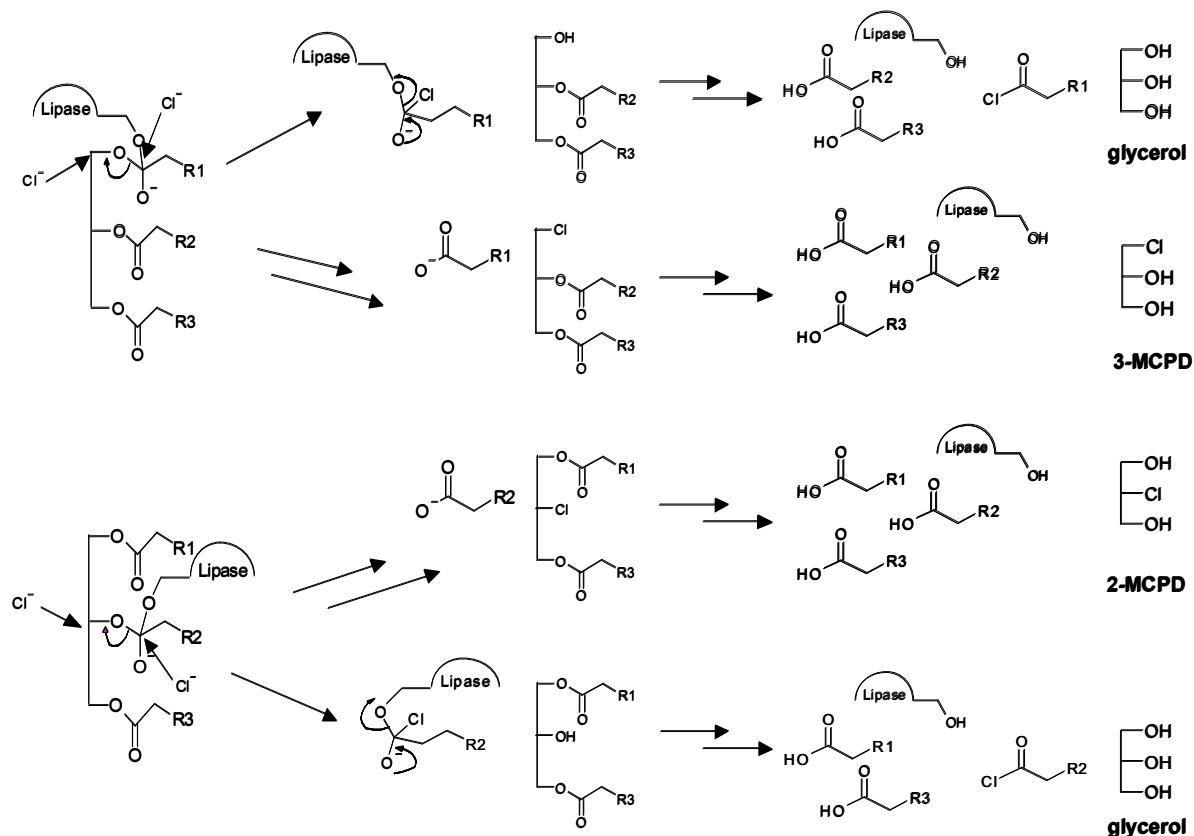
Figure 2. Recently proposed enzyme-catalyzed pathway leading to the formation of monochloropropanols (adapted from Robert *et al*. [17])

As several pathways may be operative in the formation of chloropropanols, different approaches will need to be considered in mitigation research. Domestic cooking has shown that grilling and toasting produces 3-MCPD in bread and cheeses [16], and therefore – similar to the case of acrylamide – relative reduction in cooked foods will be difficult to attain. However, certain mitigation measures may be feasible in 3-MCPD formation catalyzed by the action of lipase in savoury foods. The inactivation (e.g. thermal) or removal of lipase activity in ingredients are concrete steps that may be considered. For example, native pepper with inherent lipase activity could be substituted by pepper extracts [17].

The model experiments described by Robert *et al*. [17] demonstrated a novel non-thermal pathway in the formation of chloropropanols in foods and food ingredients. In dried savoury foods that contain salts and lipids, residual lipase activity of certain ingredients will be an important parameter to monitor, as it may reflect the formation of these storage and processing contaminants over time.

ACRYLAMIDE

Background and occurrence in food

In April 2002, a report by the Swedish Authorities on the presence of acrylamide (2-propenamide) in a wide range of fried and oven cooked foods [18] attracted worldwide attention, due to the fact that acrylamide is classified as probably carcinogenic to humans (Group 2A) by the IARC [19]. Acrylamide is formed in food as a result of cooking practices, many of which have been used by mankind for many centuries. Initial surveys have shown that relatively high concentrations of acrylamide are found in high-carbohydrate foodstuffs [20, 21], such as potato chips, French fries, pan-fried potato products, and crisp bread. The parallel finding that fried meat of pork, chicken, beef or cod, sausages or hamburger contained only low amounts of acrylamide suggested that carbohydrate, but not protein-rich foods, provided the precursors of acrylamide formation [4].

Furthermore, acrylamide formation was correlated to the degree of browning, highlighting the

importance of the Maillard reaction, in particular the amino acid asparagine. Bread, especially bread crust, cereals and coffee as well as coffee surrogates were found to contain significant levels of acrylamide. Particularly cereals, coffee and crisp bread were considered as relevant sources of human exposure, since they are consumed on a regular basis by a broad group of consumers with especially high exposure in certain European countries (coffee and crisp-bread in Nordic countries, potatoes in Holland [22–24].

The exposure to acrylamide is variable, due to the differences in food consumption patterns and cooking traditions between European countries. In addition, acrylamide uptake can vary in the different population subgroups, with for example considerably higher uptake in children and adolescents that exhibit a different contribution of food categories to the overall exposure. The different exposure scenarios, however, are beyond the scope of this report.

The potential health risk of acrylamide in food has been considered by a number of government agencies and National Authorities (SCF, www.europa.eu.int) and UK FSA, www.food.gov.uk.). Following these deliberations, all available data on acrylamide have been reviewed at international level (e.g. FAO/WHO, JIFSAN workshops) by expert working groups. These have listed and identified a number of research gaps and research priorities, and once addressed would allow a better assessment of the possible health risks associated with this finding.

Mechanisms of formation

Shortly after the announcement of the discovery of acrylamide in cooked foods, numerous research groups in academia, industry, and official control laboratories commenced studies into the possible sources of this food-borne contaminant. Several hypotheses on formation pathways were discussed at the very early stages of investigations, focusing initially on vegetable oils/lipids, since the problem encompassed mainly carbohydrate-rich foods that are fried or baked.

However, much progress in the fundamental mechanistic studies has been made to date, and over 15 peer-reviewed research papers have been published so far that deal with mechanistic aspects. The major breakthrough was achieved just a few months after the first Swedish report, and several research groups [5, 6] concomitantly identified the importance of the free amino acid asparagine and the non-enzymatic browning (Maillard) reaction in the formation cascade.

The early proposal by Stadler *et al.* [5] was fragmented in terms of providing a feasible chemical route, and more concrete evidence was provided by Zyzak *et al.* [25] and Yaylayan *et al.* [26]. Both groups have shown evidence for the importance of the Schiff base of asparagine, which corresponds to the dehydrated *N*-glucosyl compound.

Under low moisture conditions, both the *N*-glycosyl compound and Schiff base are relatively stable. However, in aqueous systems the Schiff base may hydrolyze to the precursors or rearrange to the Amadori compound (Figure 3, pathway I), which is not an efficient precursor in AA formation. Even under low moisture conditions, this reaction is the main pathway initiating the early Maillard reaction cascade that leads to 1- and 3-deoxyosones, which further decompose to generate colour and flavour. This is in agreement with the relatively low transformation yield of asparagine to acrylamide, typically below 1 mol%. Alternatively, the Schiff base may decarboxylate to the intermediary azomethine ylide (Figure 3, pathway II), which after tautomerization leads to the decarboxylated Amadori compound (Figure 3, pathway III). The prerequisite for this reaction is the presence of an OH-group in β-position to the *N*-atom. As α-hydroxycarbonyls are proper precursors to yield such azomethine ylides, in contrast to α-dicarbonyls, reactants such as 1-hydroxy-2-ketones (e.g. fructose, acetol) and 2-hydroxyaldehydes (glucose, 2-hydroxy-1-butanal) generate more acrylamide than α-dicarbonyls (2,3-butanedione, methylglyoxal).

In summary, the two proposed mechanisms [25, 26] appear to be the most feasible routes to acrylamide from asparagine, assisted by a reactive carbonyl. Certain minor pathways have been suggested whose importance relative to that of asparagine must be independently determined in the pertinent foods. Further work is now warranted to unequivocally identify the proposed intermediates and precursors in food systems.

Potential strategies of control

Early data on the occurrence of acrylamide in food highlighted relatively higher amounts in carbohydrate-rich foods, including potato crisps and French fries. Consequently, research programmes
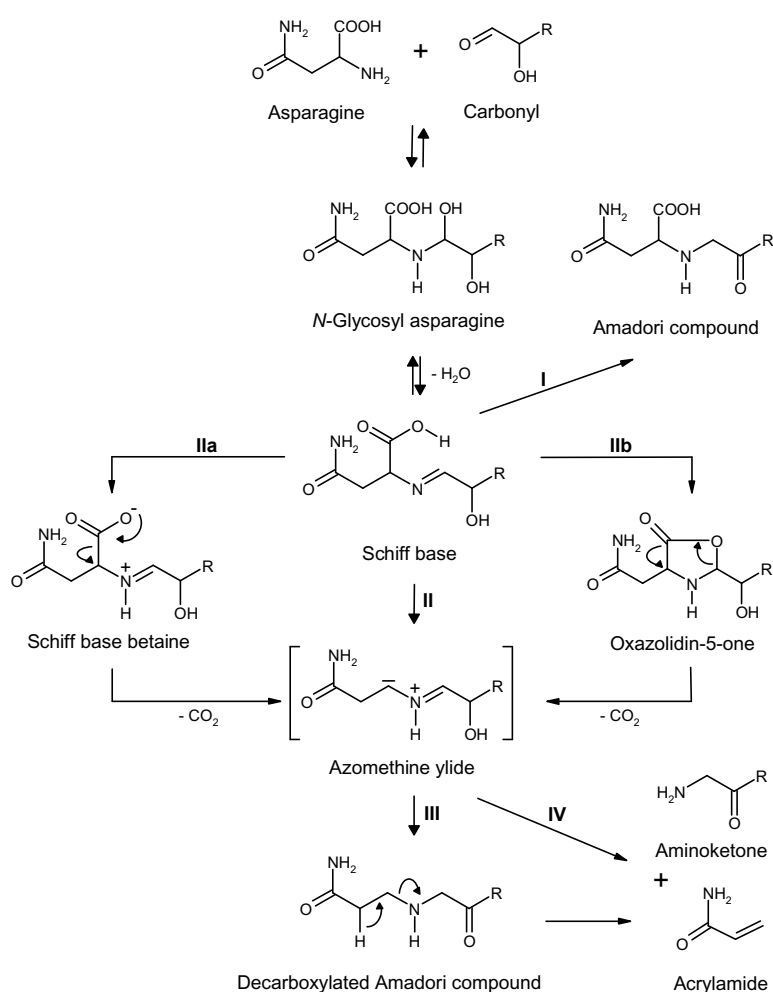
Figure 3. Formation of acrylamide from asparagine in the presence of α-hydroxycarbonyls. R represents the rest of the carbonyl moiety (adapted from Stadler *et al.* [27])

at the experimental (laboratory) and pilot trial level were established that focused on these food groups, with the goal to elucidate the key factors that may impact acrylamide formation. Expert meetings and workshops have also been held over the past 2 years involving all stakeholders to identify concrete ways to lower the amounts of acrylamide in food, e.g. the European Commission Workshop on October 20–21, 2003. A summary of the outcome of this important stakeholder meeting has been posted on the Commission website and provides guidance and recommendations to food producers, retailers, caterers, and consumers [28].

This section summarizes the key knowledge attained so far in potato products, bread & bakery wares, and coffee.

Potato products

Potato-based foods that are either baked and fried, or cooked define a wide range of different products on which much investigative work has been performed to date to determine the formation and potential control of acrylamide. Numerous possible avenues of reduction of acrylamide in potato products, in particular French fries, have been highlighted in several recent reports [29–34]. These entail controlling the temperature of storage of the raw potato, selection of certain varieties, and modifying processing (frying) conditions. However, any modifications performed on the raw material constituents will inevitably impact the Maillard reaction and its products, and concomitantly the organoleptic properties (taste and colour) of the cooked food. However, even though small scale and laboratory trials have shown that products such as French fries can be prepared with acrylamide amounts below 100 μg/kg [34], all these measures must be placed in the perspective of consumer acceptance, not forgetting those related to the supply chain management and logistics of harvesting, storage, and transport of the raw potatoes.

Bread and bakery wares

Only a few reports on the formation of acrylamide in bread and bakery products have been published to date [35–38]. In crisp bread, acrylamide concentration could be reduced by decreasing the average longitudinal oven baking temperature and increasing the baking time [35]. A similar empirical trial approach has been applied to biscuits. Acrylamide is not present in uncooked dough, but the acrylamide level rises rapidly with time. Temperature and cooking time are closely related in the baking process, as is final moisture content, that in some trials has been shown to be inversely proportional to the acrylamide content in the final product. Acrylamide formation has also been studied with regard to ingredients and formulations. The addition of whole wheat flour and bran to biscuit formulas tended to increase acrylamide in comparison with plain counterparts. Reducing the amount of the raising agent ammonium bicarbonate in formulas lowered acrylamide in plain flour matrices. The addition of lactic acid also lowered acrylamide content in plain flour matrices [35]. Experiments are ongoing to determine the relative impact of baking temperature, baking time, final moisture content and biscuit thickness on acrylamide formation.

Coffee

Compared to the many other fried, roasted and baked food products, roast and ground coffee has been reported to contain relatively low concentrations (170–351 µg/kg on a powder basis) of acrylamide [39]. Roast and ground coffee is not consumed as such, but prepared as a beverage. Coffee is prepared by the addition of hot water and subsequent filtration. Hence, calculation of the acrylamide content per cup is an important term of exposure levels [40].

Coffee is typically roasted at temperatures in the range of 220–250°C, and the roasting time and speed of roast have an important impact on the sensorial properties (aroma/taste). These are carefully fine tuned to a characteristic profile leading to a clear identity of the coffee product.

Experiments have shown that acrylamide is degraded/eliminated during roasting, and the profile of acrylamide formation during the roasting of coffee reflects this effect very clearly [35]. In coffee, acrylamide is formed at the beginning of the roasting step, and toward the end of the roasting cycle a loss of acrylamide seems to dominate. Therefore,

light roasted coffees may contain relatively higher amounts of acrylamide than dark roasted beans. However, higher roasting as a potential option to reduce acrylamide could generate other undesirable compounds and negatively impact the taste/aroma of the product. Consequently, no practical solutions are today at hand that would reduce acrylamide levels and concomitantly retain the quality characteristics of coffee, since the roasting step cannot be fundamentally changed [35].

Conclusively, it can be said that the food industry, in a joint collaborative effort, could so far show moderate successes in the relative reduction of acrylamide by several collective measures in certain foods, e.g. raw material selection, adapting processing parameters, guidance on final food preparation. On the other hand, in some foodstuffs this has been shown to be very difficult or not possible at all without introducing other risks to the consumers. As already mentioned, operational parameter changes will impact product quality characteristics (e.g. texture, taste, color) that clearly need to be taken into account.

German signal values (SV): Concept of minimizing acrylamide contents in food

In Germany, the minimization concept was introduced as a measure to monitor and encourage the reduction of acrylamide levels in foods. Analytical results obtained on a national basis were used to determine the so-called signal value, which is defined as the lowest value of the upper 10th percentile of data points within individual food categories. The upper limit of signal values is 1000 µg/kg. For individual samples that exceed the signal values, food control authorities will contact the food producers concerned and enter into the minimization dialogue to check whether ingredients or processes could be changed to minimize acrylamide contents. The Federal Office of Consumer Protection and Food Safety (BVL) will update signal values annually. This will balance the effects of seasonal fluctuations in acrylamide contents in foods and impact of seasonal variations.

To date, three signal value calculations were published based on approximately 4200 data points (Table 1). Albeit a reduction of acrylamide levels in specific food categories, these were not regarded as significant[50] due to factors relating to co-ordination of sampling, sample traceability and categorization of product groups. Therefore,

Table 1. German signal values for acrylamide (µg/kg)

Food group	Signal values		
	17. 09. 2002	31. 01. 2003	26. 11. 2003
Fine bakery ware of short pastry	800	660	575
Breakfast cereals	260	260	200
Coffee, roasted	370	370	370
Potato crisps	1000	1000	1000
Crispbread	610	610	610
French fries, prepared	770	570	570
Potato fritter, prepared	1000	1000	1000
Gingerbread and bakery ware containing gingerbread	1000	1000	1000
Thin almond biscuit	1000	710	710
Children's biscuits	n.c.	n.c.	360
Diabetic's cakes and biscuits	n.c.	n.c.	1000
Coffee extract	n.c.	n.c.	1000
Coffee substitute	n.c.	n.c.	1000

n.c. – not calculated

Source: WEB site Bundesamt für Verbraucherschutz und Lebensmittelsicherheit, Bonn, June 28, 2004. Presseinformation No. 7/2004

BVL has taken action to improve the situation. It should be emphasized that this approach is limited to products as sold on the market. Foods prepared in the home, by catering services or restaurants, are not considered. Notably, reduction of signal values for particular food categories does not directly allow a conclusion as to a reduced average exposure of the consumer.

FURAN

Background and occurrence in food

Furan (C_4H_4O) is a highly volatile chemical (b.p. 31°C) that occurs naturally and is a component of smog and cigarette smoke. Furan is also produced synthetically and employed industrially as a solvent or intermediate in polymer synthesis. Derivatives of furan have been associated with flavour of foods (although furan is not used as flavouring ingredient as such), and earlier work has reported the occurrence of trace amounts of furan in several heat-treated foodstuffs and beverages, such as canned meats, bread, and coffee [41, 42]. Recently, the US Food and Drug Administration (FDA) conducted a survey of furan in different heat-processed foods. Their results were announced on 7th May 2004 in which they identified furan in a number of foods that undergo heat treatment such as canned and jarred foods. In the 120 food samples analyzed, furan levels were found ranging from non-detectable up to maximally 125 µg/kg [9].

At this point it is important to elaborate on the term "furans", which is frequently used to describe a large class of compounds of varying structures including, for example, the nitrofurans (antimicrobial compounds). In addition "furans" is also used as an abbreviation for the highly toxic dioxin-like dibenzofurans. These classes of compounds are clearly different in structural, toxicological, and exposure perspectives.

Little is known about food-mediated exposure to furan. The limited knowledge available on formation, volatility and occurrence suggests that furan is likely to occur in closed food products subjected to heat treatment (e.g. canned and jarred foods). There is not enough occurrence data available to us at the moment to estimate the exposure to furan from food. Preliminary data from FDA [9] suggest that the highest exposures could result from the consumption of certain manufactured infant products. The International Agency for Research on Cancer (IARC) evaluated furan in 1995 [43]. It was considered that there is sufficient evidence

in experimental animals for the carcinogenicity of furan. Since no data are available that would suggest that the mechanisms thought to account for tumor induction by furan in experimental animals would not operate in humans, IARC classified furan as possibly carcinogenic to humans (Group 2B). The mechanism of furan carcinogenicity (genotoxic versus non-genotoxic) is a key information required for deciding upon the approach to be applied for evaluating the health significance of furan in food.

The US FDA is currently requesting the submission of data and information on furan, including the occurrence in food, sources of exposure other than food, mechanisms of formation of furan in food, and on the toxicology of furan.

Mechanisms of formation

The source of furan in food can be either through environmental contamination or through natural formation resulting from thermal processing. Although little is known about the mechanism of furan formation in food, the primary source is thermal degradation and rearrangement of particularly carbohydrates [41]. Recently, researchers have brought forward the hypothesis that furan may result from either an oxidation of polyunsaturated fatty acids at high temperatures and/or from the decomposition of ascorbic acid derivatives [44].

Potential strategies of control

Furan is a volatile molecule and levels fall as soon as the bottles or cans are opened. It is thought to be a product of heat processing. No evident measures to control or reduce furan during the heating of foods have been identified to date.

CONCLUSION

The discovery of the food-borne contaminant acrylamide in foods has launched considerable research efforts on a global scale to fill the current gaps in the scientific knowledge base. It has also led to a consensus amongst all stakeholders that there is an urgent need of a better understanding of the impact of thermal processing on the safety of food. Analytical techniques have greatly improved over the past decade, enabling the detection of very low amounts of "undesired" food constituents. Many of these compounds are unavoidable in our diet,

and may be formed both under domestic cooking conditions and during industrial processing. The current list of compounds that have been identified to be of apparent concern in our daily diets will most likely lengthen, and the latest candidate, furan, has just recently been added.

Consequently, a major challenge is to determine the actual health risk that process-related compounds pose to the human population. For compounds such as 3-MCPD that are non-genotoxic, sufficient data are available to establish a safe level of intake, leading to regulatory decisions to which industry must abide. In the case of compounds acting through a genotoxic mechanism, new approaches in the risk assessment may be warranted [45], such as dose-response modelling that would allow the establishment of a margin of safety also for these chemicals.

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