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ORIGINAL PAPER

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Heat and mass transfer in chicken breasts – effect on PhIP formation

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Abstract Heterocyclic amines are mutagenic/carcinogenic compounds that are found in cooked meat and fish. These compounds are of concern in the aetiology of human cancer and therefore it is important to minimise their formation during cooking, and their intake. PhIP (2-amino-1-methyl-6-phenylimidazo[4,5-*b*]-pyridine, CAS no: 105650–23–5) is one heterocyclic amine that is found at high levels in cooked chicken. Chicken breast was cooked to a centre temperature of 72 °C using the following cooking methods: boiling, oven roasting, oven roasting in a special roasting-bag or in a clay pot, broiling, deep-frying and pan-frying. The temperature on the surface and at the centre was monitored by thermocouples during cooking, and these data, together with drip loss determined by means of weight reduction, were used to create temperature profiles and to calculate cook-values and rate of drip loss. The samples were analysed for PhIP using solid-phase extraction and HPLC. PhIP was detected in the broiled (0.07 ng/g), deep fried (0.02 ng/g) and pan-fried (0.04 30 ng/g) chicken breast. The cooking temperature and rate of drip loss had great impact on crust formation during pan-frying, and greatly affected the amount of PhIP formed. High temperature and high rate of drip loss were found to be most favourable for the formation of PhIP.

Keywords PhIP · Food mutagens · Chicken · Heat transfer

Introduction

Epidemiological studies have shown diet to be an important factor in the global variation of human cancer rates [1]. After the finding of potent mutagenic activity in the charred surface of broiled beef and fish [2], work began to identify and quantify mutagenic substances in cooked foods. The mutagenic substances were later identified as heterocyclic amines, and several of them have been proven to be carcinogenic in long-term animal experiments. An increasing number of studies indicate that humans absorb and metabolise heterocyclic amines, resulting in DNA adduct formation (see reviews [3, 4]). It has recently been suggested that one of the compounds, 2-amino-1-methyl-6-phenylimidazo[4,5-*b*]-pyridine (PhIP) plays a significant role in human carcinogenesis [5]. As PhIP and other heterocyclic amines are candidates in the aetiology of human cancer [6], increased knowledge on the conditions for their formation is required in order to minimise their occurrence in cooked foods and thus our intake of them. It is therefore important to study the formation of heterocyclic amines in relation to heat and mass transfer and to use the data for the simulation and prediction of heterocyclic amine formation. Many previously reported studies have been performed under poorly controlled cooking conditions or at high temperatures and long cooking times.

The aim of the present study was to investigate heat and mass transfer and the formation of PhIP in chicken using various domestic cooking methods under well-controlled cooking conditions. Chicken was selected because the consumption of chicken is increasing. Chicken is one of the most important muscle food sources today, and cooked chicken is known to be a major source of PhIP [7].

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Materials and methods

Food samples. Chicken fillets from the same production batch were obtained from a local slaughterhouse. The relationship between weight and surface area of the raw fillets was determined. Chicken fillets were analysed for heterocyclic amine precursors as described by Arvidsson et al. [8]: free amino acid analysis with ion-exchange chromatography and creatine, creatinine and glucose with enzymatic methods.

Temperature measurements. Three K-type thermocouples were used to measure the temperature in each fillet: one thermocouple was inserted into the centre of the fillet and two were fixed just below the upper and lower surface. In the pan-frying experiments a fourth thermocouple was placed between the fillet and the frying pan. The thermocouples were connected to a data logger and the temperature was recorded every 10 s.

Drip loss. The drip loss of liquid and its relation to time and centre temperature was estimated in chicken fillets cooked in a roasting bag in an oven at 200 °C for 3–14 min. For each data point, three fillets were used, and they were weighed before and after cooking. To estimate the amount of liquid passing through the crust during cooking, the drip loss per unit area was calculated.

Cooking experiments. In the first set of experiments, chicken fillets were cooked to a centre temperature of 72 °C using the following cooking methods: boiling (100 °C), oven roasting (200 °C), oven roasting in a roasting bag (200 °C) or in a unglazed clay pot (200 °C), broiling (180 °C), deep-frying (140 °C) and pan-frying (160 °C). The cooking temperatures used in the different methods were chosen from Swedish cookery books. Three fillets were cooked with each cooking method.

In the second set of experiments, chicken fillets (115±5 g) were fried at 175, 200 and 225 °C in a frying pan. When the centre temperature reached 50 °C, the fillets were turned over and fried until the centre temperature reached 72 °C. Three fillets were fried at each temperature, one at a time. For each fillet, 10 g margarine was added, and frying was started when the temperature of the fat had reached the desired frying temperature. The frying pan was cleaned between each cooking session to eliminate cross contamination. The fried fillets were weighed, and the weight loss was calculated. The outer layer (crust), about 2–3 mm, of the fillets was removed using a scalpel and stored at –18 °C until analysed. The crusts from all fillets fried at the same temperature were pooled for heterocyclic amine analysis.

Chemicals. Solvents and chemicals were of HPLC or analytical grade. Water was passed through a Milli-Q water purification system (Millipore, Bedford, MA, USA). PhIP (2-amino-1-methyl-6-phenylimidazo[4,5-*b*]pyridine) was purchased from Toronto Research Chemicals (Toronto, Canada) and used as a reference compound. Materials for solid-phase extraction were obtained from Sorbent AB (Västra Frölunda, Sweden) and Scantech Lab (Partille, Sweden).

Extraction and quantification of PhIP. Samples were extracted and analysed using reverse-phase HPLC [9] with minor modifications [10]. Extraction recovery rates for PhIP were determined by the addition of a known amount of synthetic PhIP to one sample extracted in parallel with two unspiked samples. The extraction recovery rate was 70%. PhIP was identified and quantified using retention times and the spectra from the synthetic standard of known concentration, analysed under the same conditions.

Calculations. Cook values (C values) were calculated at the centre point and on the surface of the meat using the temperatures recorded with the thermocouples. A standardised z value for meat/chicken of 33 °C was used [11]. The temperature profile in the meat was calculated for pan-frying, deep-frying, boiling and broiling, using a computer program[12].

Results and discussion

Different cooking methods

When chicken fillets were cooked using various methods, PhIP was found only in the broiled (0.07 ng/g) and deep-fried fillets (0.02 ng/g), and in pan-fried chicken at 160 °C (0.04 ng/g) (all values are calculated as ng/g cooked fillet). The weight loss ranged from 9% when cooking in a clay pot, up to 22% when roasting in a roasting bag.

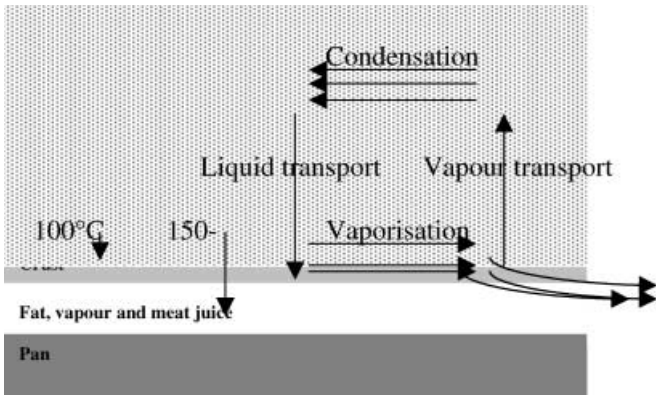

Fig. 1 Transport of water in meat during pan-frying

Cooking of meat involves different types of heat flow [13]. In the *oven*, the heat is transferred to the meat by convection through the air and radiation from the walls. During *boiling* and *deep-frying*, a liquid surrounds the meat and the heat is transferred by convection. During *pan-frying*, the heat is transferred to the meat by means of both conduction and convection, through a layer of fat and water. *Inside* the meat, conductive heat transfer dominates.

All kinds of heat transfer are dependent on a temperature gradient, but the type of heat transfer highly affects the rate of heat flow. The heat flow, Q, *to the meat surface* can be written as $Q=hA(T_1–T_2)$, where h is the apparent heat transfer coefficient, A is the surface area of the meat, T_1 is the ambient temperature and T_2 is the temperature of the meat surface (see Fig. 1). The apparent heat transfer coefficient is used to estimate the efficiency of heat transfer, and varies from about 20 W/m^{2}K in an oven up to 10,000 W/m^{2}K in boiling water. *Inside the meat*, the heat transfer follows the "stationary heat transfer equation" and will be rate-determining. This means, for example, that the cooking time required to reach a certain centre temperature is not significantly affected by the pan temperature, but the heat transfer inside the meat.

To evaluate the degree of heat treatment using the different cooking methods, the C value or cook value was calculated. The C value refers to the combined influence of time and heat treatment. The C values at the centre of the fillets were similar, irrespective of cooking method, indicating the same heat exposure. At the surface the C values differed, but were not related to PhIP formation.

Figure 2 shows the simulated temperature profiles from one surface through the centre to the other surface, when the centre temperature had reached 72 °C. Cooking methods, in which the chicken fillets were exposed to a high surface temperature, e.g. pan-frying and deep-frying, also yielded the highest levels of heterocyclic

amines. It should be noted that the model does not take into consideration the evaporation process in the crust.

Pan-frying at three different temperatures

Based on the results of the above experiments using different cooking methods it was decided to focus on pan-frying since pan-frying is a common way of preparing chicken fillets and the heating conditions are easy to control. In the second set of experiments, PhIP was detected in all samples. The amount of PhIP increased from 0.7 ng/g at 175 °C, 10.0 ng/g at 200 °C and reached 29.7 ng/g at 225 °C (Table 1). This is in agreement with previous studies: not detectable – 10 ng/g levels of PhIP for chicken breasts fried for 30 min at 150–225 °C [14] and not detectable – 10 ng /g for chicken breasts fried for 15–25 min at 160–220 °C [15]. Sinha et al. [7] reported considerably higher amounts of PhIP, 12–70 ng/g in chicken fillets fried for 14–36 min at about 200 °C, whereas no PhIP was found in another study [16] on chicken breasts fried for 12 min at 190 °C. The explanation of the different results could be the different cooking temperatures and times.

The temperature profile in the crust varied in the different experiments. Figure 3 shows the temperature in the crust for two different experiments performed at 200 °C. When the fillet was first put in the pan, the pan temperature dropped, and then increased continuously until the filet was turned. In one of the experiments (Fig. 3), the thermocouple in the crust showed temperatures that were about 10 °C below the temperature of the pan. In another experiment (Fig. 3), the thermocouple in the crust showed a constant temperature of about 100 °C. The difference could have several explanations, but the most likely is that the thermocouples were inserted at different positions. One was placed nearer the surface and the other deeper in the fillet, i.e. in the evaporation zone, where the temperature is 100 °C. Thus, the thermocouples showed different temperatures [13]. Only some regions in the outermost part of the meat are completely free from water and as long as water is present, the temperature cannot rise above 100 °C. The temperature profiles in Fig. 3 clearly show the presence of an evaporation zone. This zone will increase in depth during cooking, i.e. a crust will be formed, in which the PhIP formation takes place. The crust acts as an insulating layer and the heat transfer inside the meat will slow down. In contrast to the crust, the temperature profile at the centre of the fillet did not vary to the same extent.

The fillets differed in weight (115±5 g), area (185± 8 cm^2) and thickness (27±5 mm), which caused the

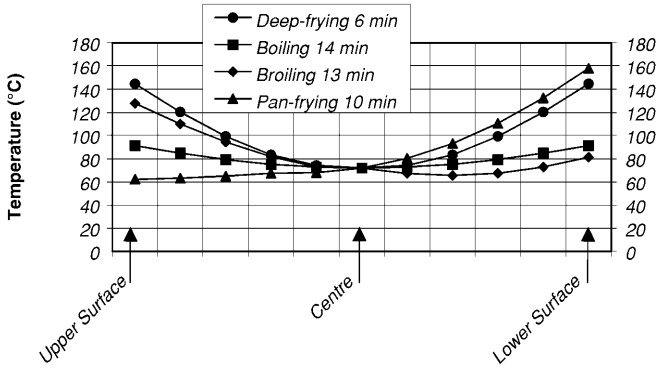

Fig. 2 Simulated temperature profiles for chicken breasts cooked to a central temperature of 72 °C under different cooking conditions

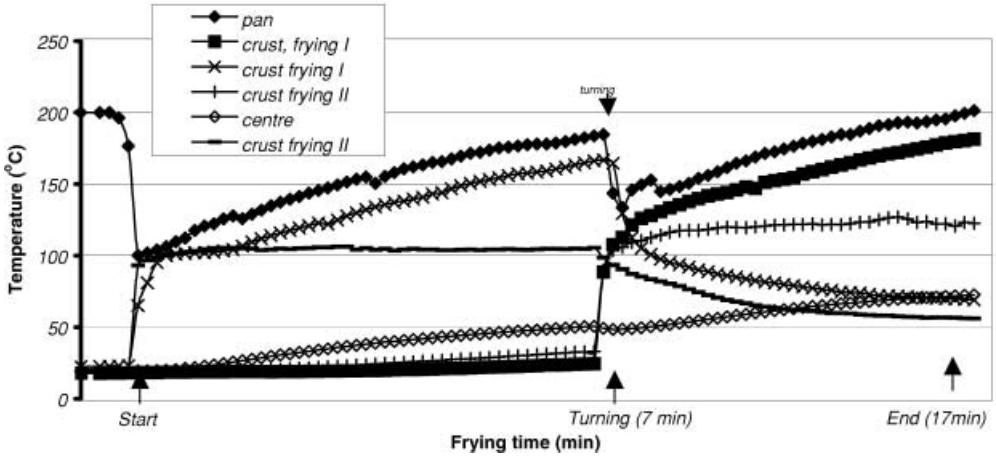

Fig. 3 Temperature in chicken fillet during pan-frying at 200 °C

Table 1 Cooking data for the chicken breast pan-fried in this study

Frying temperature (°C)	Frying time (min)	Weight loss (%)	Dry matter in the crust (%)	Dry matter in the crumb (%)	PhIP (ng/g cooked fillet)
175	16	20.5±1.2	54.7	29.4	0.7
200	18	26.2±1.0	55.1	30.3	10.5
225	12	25.3±1.3	57.8	33.9	29.7

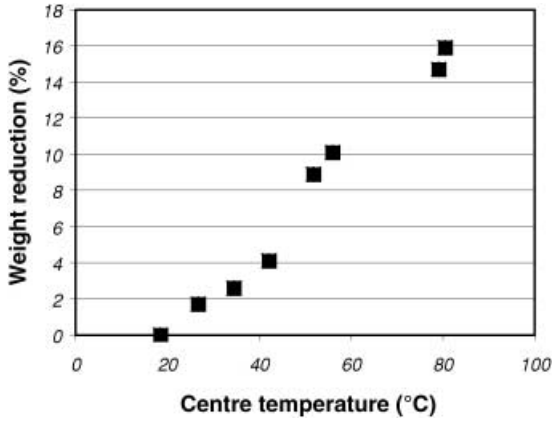

Fig. 4 Weight reduction in chicken fillet as a function of centre temperature during cooking in a roasting bag in an oven

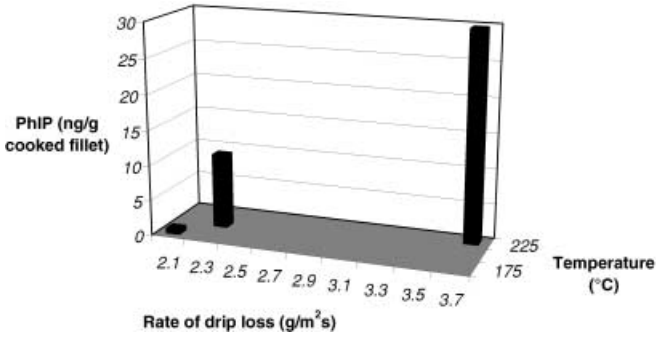

Fig. 5 PhIP formation during pan-frying, as a function of temperature and rate of drip loss

cooking time to vary between 12 and 18 min for the fillets fried at different temperatures (Table 1). However, similar C values were obtained at the centre points, which means that the centres of the fillets were exposed to the same heat treatment, independent of the frying temperature. Heating of meat will cause protein denaturation and loss of fat and water. Heat is supplied to the surface and transferred to the centre, creating a temperature gradient in the meat (Fig. 1). As the temperature at the surface increases, the partial pressure (p) of water increases, according to Charles's law, p=constant×T. The temperature and the partial pressure are highest near the surface and vapour will start to move towards the centre to reduce the pressure difference. At the centre, where the temperature is lower, vapour will condense and release heat. This will also increase the water content at the centre and water will start to migrate towards the surface to reduce this difference. Some vapour will also diffuse out of the meat. Water transport is, however, much slower than vapour transport [17]. The dry matter in the crust and in the crumb were not affected by the frying temperature. The weight loss varied from 17 to 30% for the three temperatures, which is normal [18]. No correlation was observed between the weight loss and PhIP formation.

Rate of drip loss

As PhIP formation was not directly connected to pan temperature or weight loss, we started to search for another parameter affecting the formation. Cooking in a roasting bag was used to estimate indirectly the rate of drip loss for the pan-frying experiments, since pan-frying and cooking in a roasting bag gave a similar "drip loss" (18 and 22%) in the first set of experiments. Figure 4 shows the relation between the temperature at the centre of the fillet and the loss of liquid (g) during cooking in a roasting bag. It can clearly be seen that liquid starts to leave the fillet and that the fillet loses most of its liquid when the centre temperature rises above 45 °C. To calculate the rate of drip loss, the assumption was made, from these data, that drip loss occurs at centre temperatures above 45 °C. The drip loss per unit area was divided by the cooking time during which the centre temperature increased from 45 °C to 72 °C. This average value was denoted "the rate of drip loss".

The rate of drip loss was calculated for the pan-fried fillets. Figure 5 shows the relation between rate of drip loss, temperature and formation of PhIP. It is obvious that a high temperature combined with a high rate of drip loss is most favourable for the formation of PhIP.

Conclusions

In conclusion, PhIP was found in the broiled (0.07 ng/g), deep-fried (0.02 ng/g) and pan fried (160 °C) (0.04 ng/g) fillets, while no PhIP was found in the chicken that was oven-roasted, boiled, oven-roasted in a clay pot or oven-roasted in a cooking bag.

The cooking temperature and rate of drip loss have considerable impact on crust formation during pan-frying. These parameters also greatly affect the amount of PhIP formed; a high temperature and high rate of drip loss are most favourable for the formation of PhIP.

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