Effect of Various Processing Methods on the 
Physical Properties of Cooked Rice and on in vitro 
Starch Hydrolysis and Blood Glucose Response in 
Rats

The effects of various cooking methods on the physical and structural properties 
cooked rice, on the in vitro hydrolysis of the contained starch and on blood glucose 
response in rats were investigated. At optimum cooking state, a larger filamentous 
network was formed and most of the starch granules were fragmented, furthermore the 
samples heated by microwave and electric cooker showed a more compact structure 
compared to those treated in an autoclave or stone pot. The highest degree of gelati-
nization (DG) was observed in the sample treated in an autoclave (75.2%), followed by 
stone pot (71.1%), electric cooker (66.9%) and microwave oven (64.6%). The highest 
firmness (3.49 N) was observed in cooked rice heated by microwaves and no signifi-
cant differences \((p > 0.05)\) were found between the other samples. All cooked rice 
samples showed increased pasting temperatures and decreased peak viscosity com-
pared to those of raw rice flour. The starch hydrolysis rates and their kinetic constants 
of cooked rice samples increased with increase in DG, and relatively higher values 
were observed in samples treated in the autoclave and stone pot. There was a signifi-
cant difference in the blood glucose content depending on cooking methods, and the 
highest glucose level was observed in the sample heated by autoclaving.

**Keywords:** Cooking method, rice; Structure of cooked rice; Starch hydrolysis rate; 
Texture and pasting properties; Blood glucose

1 Introduction

During cooking starch is gelatinized, losing its crystalline 
analysis and becomes prone to hydrolysis by 
enzymes. Starchy foods differ in the rates at which they 
are digested and absorbed. The different glycemic effects 
of starchy foods have been the subject of chronic dis-
eseases such as obesity, cardiovascular disease, and dia-
betes [1, 2, 3]. The continued intake of high-glycemic load 
meals is proposed as dietary factor that favor the develop-
ment of chronic diseases. Both rate and extent of 
starch hydrolysis in vitro are regarded as an important 
determinant of metabolic responses to complex carbo-
hydrate in vivo [4, 5]. The extent of starch hydrolysis has 
been extensively studied in the past [6, 7, 8], and the 
extent of digestibility with respect to enzymatic hydrolysis 
can be affected by intrinsic factors such as the different 
native structures and extrinsic factors such as the pres-
ence of enzyme inhibitors and the processing methods. 
The difference in starch digestibility according to various 
cooking methods [9, 10] may be attributed to some other 
factors such as starch gelatinization, structural modifica-
tion [11] and the extent of Maillard reactions in the pres-
ence of proteinaceous materials [12, 13]. The processed 
starch is made up of at least two fractions: one digestible 
and one indigestible, so-called resistant starch (RS). The 
amount of RS depends on the degree of gelatinization 
and retrogradation during cooling of the cooked food [14, 
15]. Resistant starches are not absorbed in the small 
intestine because they are resistant to enzyme digestion, 
but have various physiological effects such as the reduc-
tion of plasma cholesterol, alteration in microbial popula-
tions, and increase in large intestinal short-chain fatty 
acid production [16, 17].

In Asia, at present the rice is consumed and processed 
using various processing methods such as microwave, 
electric and pressure cooking, as well as conventional 
methods. The cooking of rice was an art that had to be 
learned, but the advent of rice cookers has made this 
culinary task much easier. The main functions of cooking 
are an improvement of the digestibility of starch, whole-
someness, and texture of cooked rice. The heat transfer 
characteristics are different according to the cooking 
methods, and this will cause a difference of micro-
structure of starch. This can influence the rate of digestion and quality of cooked rice. The quality evaluation of cooked rice has been mainly reported for textural property and sensory evaluation [18, 19, 20].

The present study was undertaken to investigate the effect of different processing methods on the enzymatic hydrolysis and the physical and structural property of cooked rice. In addition, the effect of the ingestion of different cooked rice on blood glucose responses in rats was studied.

2 Materials and Methods

2.1 Materials

The rice used was a Korean rice cultivar, Suwon 355 (Ilpumbyeo), containing 7.8% protein and 75.2% carbohydrate and harvested in 2002.

2.2 Preparation of samples

2.2.1 Soaking

Rice (Oryza sativa L.) was soaked in distilled water for 1 h at 25°C, and the rice-to-water ratio used was 1:5 (w/v). The soaked rice was rinsed with distilled water and drained. The soaked rice was cooked with various processing methods (microwave oven, electric cooker, autoclaving, and stone pot (traditional rice cooker in Korea). In all cooking methods the ratios of sample to distilled water were 1:1.2 (w/v).

2.2.2 Determination of optimal cooking time and degree of gelatinization (DG)

During cooking the temperature profiles of soaked rice were measured using a programmable temperature data logger (EBI-125A, ebro Electronic GmbH & Co. KG, Ingolstadt, Germany) and interface (EBI-KSY-AE 2000). The optimal cooking times at each cooking method were determined as samples showing maximum DG. The samples having various DG (20, 40, 60 and maximum percent) at each cooking method were prepared by measuring the reducing sugar corresponding to the enzymic degradation of gelatinized starch [21]. Samples of the rice cooked with various cooking methods were taken at various DG to be analyzed. The samples were frozen in a freezer at a temperature of −70°C and then freeze-dried in a freeze dryer (Ilshin Co., Korea) operating at −50°C and 1.33 Pa. The dried samples were passed through an 80 mesh (180 μm) sieve. The powdered samples were either tested immediately or stored in desiccators until testing.

2.3 Scanning electron microscopy (SEM)

The freeze-dried cooked rice samples were directly mounted on circular aluminum stubs covered with double-sided sticky tape, coated with 10 nm gold, then examined and photographed in a JEOL (JSM-840A) scanning electron microscope (JEOL, LTD, Tokyo, Japan) at an accelerating voltage of 20 kV. The samples were measured with the use of the calibrated scale bar on the micrograph.

2.4 Texture properties of processed rice

Twenty cooked rice granules from each run of the sample equilibrated for 1 h in closed plastic bottle at 25°C were utilized to measure the firmness, cohesiveness and
adhesiveness of cooked rice granules using a texture analyzer (TA-XT2, Stable Micro Systems, Surrey, England). Analysis of textural characteristics was based on the procedure of Mua et al. [22]. Each cooked rice granule was compressed to 30% deformation of its original height with a 5 mm diameter probe at a constant speed (1.0 mm/s). Each test sample was compressed twice, each compression being followed by decompression. The time interval between the end of the first compression and the second compression was 3 s. The first peak force (newtons) was termed firmness, and the negative force area of the curve during retraction of the probe was termed adhesiveness (10^{-3} \text{ J}). Cohesiveness is obtained by dividing the area of the second compression by the area of the first cycle. Results reported here are averages of the measurements.

2.5 Pasting properties

Pasting profiles were obtained using a Rapid Visco Analyser (RVA-3D, Newport Scientific, Warriewood, Australia). The freeze-dried rice flour (2.58 g, db) was suspended in distilled water and adjusted to a total weight of 28 g. The samples were equilibrated at 50°C for 1 min and then heated at a rate of 6°C/min to 95°C and maintained at that temperature for 5 min before cooling to 50°C at a rate of 6°C/min. A constant 160 rpm spindle speed was used. From the resulting pasting curve, temperature at initial viscosity increase ($T_i$), peak viscosity ($PV$), time to peak viscosity ($P_t$) (time at $PV$ – time at initial viscosity increase), hot paste viscosity ($HPV$), breakdown viscosity ($BV$) ($PV$ – $HPV$), cooled paste viscosity ($CPV$), and setback viscosity ($SBV$) ($CPV$ – $HPV$) were calculated.

2.6 In vitro Starch hydrolysis with amyloglucosidase and its kinetic constant

The hydrolysis rate of rice starch was tested at 40°C, in 0.2 M sodium acetate buffer (pH 5.4), using amyloglucosidase (EC 3.2.1.3, Sigma A-7255, Sigma, St. Louis, MO) as hydrolytic enzyme [23]. The samples (100 mg) were incubated with amyloglucosidase solution (about 70 units). Samples were withdrawn at timed intervals (from 0 to 60 min) and analysed for reducing sugar (D-glucose) with 3,5-dinitrosalicylic acid reagent. The absorbance of the solution was measured at 550 nm with glucose used as a standard. Percent hydrolysis was calculated as milligrams of glucose from standard curve per milligram of starch x 100. Also, a zero order kinetic model [24] has been used to evaluate the kinetic constants of rice starch hydrolysis according to the cooking methods. This type of kinetics is expressed by the following equation:

$$C = C_o + k_o t$$

where $C$ is the variable glucose content studied at time $t$, $C_o$ is the value at time zero, and $k_o$ is the zero order kinetic constant.

2.7 Blood glucose assay in rats

Male Spraque-Dawley rats, four weeks old, weighing on average 90 g were housed in individual cages at 21-25°C with 12-h day/night cycle and had free access to water and standard chow for 5 days. After adaptation to standard chow, the rats were divided into four groups on the basis of body weight. The rats were left fasting for 24 h in
individual metabolic cages. Then the rats were gavaged via stomach tube with 10 mL of the cooked rice solutions. The cooked rice solutions provided 200 mg of dry matter per 100 g of body weight. To determine plasma glucose levels, blood samples were collected from the tail vein of each rat at 0, 30, 60, 90, 120, and 180 min after gavaging. Blood was collected in 0.1 mL aliquots from the tail vein, deproteinized with 0.34 M perchloric acid and centrifuged for 10 min at 2786 g. Plasma glucose was immediately analyzed by the glucose oxidase method [25]. The areas under the curve from 0 to 180 min, ignoring the area below the fasting level, were calculated by the trapezoidal rule.

2.8 Statistical analysis

Analysis of variance (ANOVA) was performed, and difference among samples was determined using Duncan’s Multiple Range Test using the Statistical Analysis System.

3 Results and Discussion

3.1 Time-temperature profile curves

Time-temperature curves for the center position of the samples during cooking by various cooking methods are shown in Fig. 1. Significant differences for temperature gradient during cooking were found between the cooking methods. The reason for these differences in temperature gradient was considered to be the difference in heating mode. The time periods for cooking of rice using microwaves, stone pot, electric cooker and autoclave were 9 min 36 s, 15 min, 25 min and 45 min, respectively. These time periods are for the optimum cooking conditions in view of extent of gelatinization and texture. The temperature of rice heated by microwave energy increased more rapidly than those of the other methods, whereas that of rice heated by autoclaving (pressure cooking) was the most slowly increasing. These different heating patterns can cause the differences of the physical structure of cooked rice. So, the speed of the temperature elevation in the heat treatment process of the soaked rice may affect the kinetic constant and rate of starch hydrolysis, texture, and pasting properties due to the differences in microstructure of starch (see below).

3.2 Microstructure of cooked rice

Scanning electron micrographs of cooked rice heated with different cooking methods are presented in Figs. 2(a)-(d). Morphological changes were pronounced regardless of cooking methods as the degree of gelatinization (DG) of samples was increased. At DG of about 20%, a slight splitting of starch granules occurred (Fig. 2(a)), and the sample cooked by the electric cooker displayed larger granules. At a DG of about 40% many granules of the cooked rice were split (Fig. 2(b)). This resulted in a formation of cavities, and in particular the samples heated by stone pot and autoclave showed many small cavities (Fig. 2(b)). At DG of about 60%, in case of the samples heated by microwave and electric cooker a thick and compact filamentous network was formed in the region of the granules (Fig. 2(c)), whereas a thin filamentous network was formed in the samples heated by stone pot and autoclave. At optimum cooking state, a more extended filamentous network was formed and most of the granules were fragmented (Fig. 2(d)), and the samples heated by microwave and electric cooker showed a more compact structure compared to those treated in stone pot and autoclave.

3.3 Degree of gelatinization (DG) and texture of cooked rice

Experimental results for the DG and texture of cooked rice according to cooking methods were compared (Tab. 1). The DG of the sample cooked by microwaves had the lowest value (64.6%) due to the short cooking period whereas that of the sample from autoclave cooking, having the longest cooking period, was the highest (75.2%). This result indicates that the correlation between DG of sample and cooking period is very strong. However, the reason for the higher DG (71.1%) in the sample heated for a short time (15 min) in the stone pot compared to that (66.9%) of the sample with the longer cooking period (25 min) in the electric cooker needs further studies.

The highest firmness (3.49 N) was observed in cooked rice heated by microwaves, and no significant differences (p > 0.05) were found between the other samples (Tab. 1).

<table>
<thead>
<tr>
<th>Cooking method</th>
<th>DG [%]</th>
<th>Firmness [N]</th>
<th>Adhesiveness [× 10⁻² J]</th>
<th>Cohesiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave</td>
<td>64.6</td>
<td>3.49</td>
<td>0.27</td>
<td>0.67</td>
</tr>
<tr>
<td>Stone pot</td>
<td>71.1</td>
<td>2.27</td>
<td>0.10</td>
<td>0.55</td>
</tr>
<tr>
<td>Electric cooker</td>
<td>66.9</td>
<td>2.48</td>
<td>0.15</td>
<td>0.61</td>
</tr>
<tr>
<td>Autoclave</td>
<td>75.2</td>
<td>2.11</td>
<td>0.24</td>
<td>0.54</td>
</tr>
</tbody>
</table>

1) Values within the same column with different letters are significantly different (p < 0.05).
The firmness of samples, with the exception of that of the samples from the electric cooker, decreased when the cooking period increased. The firmness and DG of samples showed an inverse trend, and this trend is similar to other studies [26, 27]. The adhesiveness of samples was not affected ($p > 0.05$) by the cooking methods, whereas the cohesiveness of samples showed significant differences ($p < 0.05$). The cohesiveness of cooked rice was similar to the hardness of the samples, and the sample heated by microwave energy had the highest value (0.67). Overall, the cooking method was the important factors influencing the DG and texture of cooked rice. This is probably due to the difference in microstructures of the samples (Fig. 2(d)).

### 3.4 Pasting properties of cooked rice flours

The RVA pasting curves of cooked rice flours and raw rice flour are given in Fig. 3, the viscosity parameters evaluated are listed in Tab. 2. The RVA curve (Fig. 3) of raw rice flour displayed the highest peak among all the samples. Heat treatments of raw rice by various cooking methods resulted in increased pasting temperatures and decreased peak viscosity. The drop in peak viscosity was more severe for samples treated with an autoclave than with other cooking methods. These decreases in peak viscosity can be attributed to the changes of granular structures during the gelatinization. Katopo et al. [28] reported that under the pressure treatment, the native crystalline structure was partially altered and its pasting properties were changed. The mean initial swelling temperature ($T_i$) was not observed for the sample treated in an autoclave. We think that the reason for this was that the crystalline structure was disrupted during autoclaving. The samples treated with the other cooking methods showed no predominant difference in their $T_i$. The mean breakdown viscosity ($BV$) of the pressure-treated sample (39 RVU) was considerably lower than those of the other samples (73 -372 RVU). This is because of the small PV value (142 RVU) of the former compared with the others (275 – 535 RVU). At BV, the swollen granules are disrupted further and amylose molecules will generally leak out into the solution and align in the direction of the shear. The
Fig. 3. RVA pasting curves of the cooked rice prepared with different cooking methods.

Tab. 2. Pasting properties of the cooked rice prepared with different cooking methods.

<table>
<thead>
<tr>
<th>Cooking method</th>
<th>Pasting parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 1)</td>
<td>69.2</td>
</tr>
<tr>
<td>Microwave</td>
<td>88.7</td>
</tr>
<tr>
<td>Stone pot</td>
<td>87.9</td>
</tr>
<tr>
<td>Electric cooker</td>
<td>91.2</td>
</tr>
<tr>
<td>Autoclave</td>
<td>–</td>
</tr>
</tbody>
</table>

1) Control = raw rice flour.
Values within the same column with different letters are significantly different ($p < 0.05$). Where: $T_i =$ pasting temperature; $PV =$ cold paste viscosity; $P_t =$ time to peak viscosity; $HPV =$ hot paste viscosity; $BV =$ breakdown viscosity; $CPV =$ cold paste viscosity and $SBV =$ setback viscosity.

setback viscosity (SBV) also followed the trend of BV. The highest SBV (235 RVU) was recorded for raw rice flour, and the lowest (38 RVU) was recorded for the sample treated with an autoclave. This result showed an intimate relation with the corresponding DG (Tabs. 1 and 2). Overall, these pasting properties can be attributed to the differences of physical structure of rice starch treated with various cooking methods.

3.5 In vitro hydrolysis rate and its kinetic constant

Hydrolysis rates of all samples are illustrated in Fig. 4. The hydrolysis rate of sample treated with microwaves was marginally lower than that of the other samples. The effect on hydrolysis rate was significantly enhanced by autoclaving. Similar results from barley flour have been reported by Xue et al. [29]. The sample treated with the stone pot, having a relatively short cooking period, showed a higher hydrolysis rate than that of the sample treated with the electric cooker. In spite of relatively short heating times, the rice starch granules treated in the stone pot are more gelatinized and partly solubilized than those heated by the electric cooker. This explains the great improvement of starch hydrolysis attained after processing in the stone pot. In general, changes in starch hydrolysis rate or digestibility were correlated with the differences in disruption of crystalline regions due to the various processing methods [30, 31].

The effects of cooking methods on hydrolysis kinetic constants of all samples are shown in Fig. 5. The highest kinetic constant was determined for the sample treated in the autoclave (27.9), followed by stone pot (27.2), electric cooker (23.6) and microwave oven (22.7) in descending order. This trend was coincident with that of degree of gelatinization. Overall, the starch hydrolysis rate and
physical properties of cooked rice samples were influenced by the difference in their microstructures, which were caused by the different processing methods.

### 3.6 Glucose responses in rats

The glycemic responses (measured as the average area produced under the glycemic curve) in rats 180 min after ingestion of the cooked rice prepared by different cooking methods are given in Fig. 6. There was a significant difference in the blood glucose levels between the rats fed with the sample obtained by autoclaving and the samples gained by other cooking methods. This suggests that the sample treated by autoclaving was more susceptible to enzymatic action, as observed by Xue et al. [29]. These in vivo results corresponded to the in vitro starch hydrolysis. But this trend decreased as the degree of gelatinization (DG) was increased, and the areas under the glycemic curve were not significantly different at 20 and 40% of DG, except for the sample obtained by autoclaving. The highest glucose level in rats fed the autoclaved rice solution can be attributed to the sufficient heating time and heat treatment at high temperature (120°C). Englyst et al. [2, 5] reported that the rate of digestion of the food was an important determinant of glycemic response. Also the
nature of the starch, particle size, and the presence of fiber, fat, and proteins were all found to result in differences in the glycemic response [32, 33]. The information about the differences between the glycemic responses of rice by different cooking methods is useful and a necessary supplement to food tables in planning diets in our regions.

4 Conclusions

The structural differences of cooked rice caused during heating in water by different cooking methods affected the physical properties, in vitro starch hydrolysis rate and blood glucose response in rats. The samples heated by microwaves and in an electric cooker showed a more compact structure than that heated in an autoclave. The influence of the cooking method on the degree of gelatinization (DG) of samples followed the order: microwave < electric cooker < stone pot < autoclave. Heat treatments of raw rice by various cooking methods resulted in increased pasting temperatures and decreased peak viscosity, and particularly the difference in peak viscosity was severe in case of the sample treated with an autoclave. Overall, the texture (firmness and cohesiveness) and starch hydrolysis rate of samples had an intimate relation with their DG. The higher the DG of a sample the lower the firmness and cohesiveness, but the starch hydrolysis rate showed an inverse trend. This study suggests that the cooking method of rice is an important factor for the starch digestibility and microstructure of cooked rice.

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References


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