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Postprandial Glucose and Insulin Responses to Processed Rice Products in Normal Subjects

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Abstract

The influence of physical forms of gelatinized rice products on enzymatic hydrolysis *in vitro* and glycemic and insulinemic responses in normal subjects were studied. Densities of garaeduk, bagsulgi, and cooked rice were 1.20, 1.18 and 1.11 g/mL, respectively, while moisture contents of garaeduk, bagsulgi, and cooked rice were 47.5, 43.1 and 66.0% (wt.), respectively. The highest initial rate of *in vitro* hydrolysis by porcine pancreatic α-amylase was observed in bagsulgi followed by cooked rice and garaeduk. However, time for complete hydrolysis seemed to reach a plateau value. Postprandial glucose and insulin responses and satiety of rice products were studied in 12 normal subjects (mean age 23.2 ± 2.4 years, 6 men and 6 women). Postprandial serum glucose and insulin levels, after consumption of the rice products, reached a peak at 30 min. Garaeduk showed significantly less incremental responses for glucose (1627.5 ± 134.9 mg · min/dL) and insulin (2041 ± 287.0 μU · min/mL) than did bagsulgi for glucose (2407.4 ± 208.3 mg · min/dL) and insulin (3582 ± 264.4 μU · min/mL). Satiety responses to the rice products were not significantly different. Therefore, it can be concluded that garaeduk may be more beneficial in controlling postprandial hyperglycemia and hyperinsulinemia than bagsulgi. These results also suggest that physical properties of starch products, acquired by the specific processing methods, affect postprandial metabolism of carbohydrate foods.

Key words: rice products, postprandial, normal subjects

INTRODUCTION

Blood glucose control is one of the major goals in the treatment of diabetes (1). Recently, it has been reported that controlling postprandial glucose in addition to fasting blood glucose is important in the treatment of diabetes (2). Since it is recommended that approximately 60% of total caloric intake be supplied from carbohydrate, types and forms of carbohydrate foods could strongly influence postprandial blood glucose levels. Foods with low glycemic indices are usually recommended to diabetic patients (3). Rice has been the staple food of most Koreans, like many other Asians, accounting for most of the daily energy intake. In Korea, rice has been processed various ways such as ordinary cooked rice, rice soup and rice cake. There are many kinds of rice cake that differ by ingredients, other than rice, and by the manufacturing process.

Bagsulgi is made by steaming rice flour in a cage, whereas garaeduk is made by extruding steamed rice flour. Enzymatic hydrolysis of native starch has been shown to be affected by the granule structure, especially, crystal type, amylose/amylopectin ratio, average molecular weight and the presence of lipids and proteins (4,5). Therefore, the rate of action of amylase on grain can be expected to be dissimilar from that on corresponding starch granules, because of the difference in surface area per unit mass between the two physical forms. Content and type of carbohydrates in a food system, degree of gelatinization, particle size, physical form of food and presence of components other than starch such as lipid, protein and fiber are considered to be dietetic factors influencing postprandial blood glucose levels (3,6). Fiber, physical form, cooking, and the possible presence of a natural amylase inhibitor were also all shown to affect hydrolysis rates of starch *in vitro* (7). As a consequence, it can be expected that postprandial blood glucose levels will be affected by physical properties resulting from specific processes during the manufacture of rice products.

The purpose of this research was to examine the influence of the physical forms of gelatinized rice, introduced by processing, on enzymatic hydrolysis *in vitro*, and glycemic and insulinemic responses *in vivo*. Postprandial blood glucose, insulin, and satiety responses to the rice products were measured in normal subjects. Preferred forms, among gelatinized and processed rice products, were suggested

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for controlling postprandial glycemic responses to rice starch.

MATERIALS AND METHODS

Materials

Polished rice, grown in the Kimhae (Kyongnam, Republic of Korea) region, was purchased from a polishing plant in Busan (Republic of Korea). Bagsulgi (steamed rice flour) and garaeduk (steamed rice flour followed by extrusion) were manufactured following a typical method (Fig. 1) at a local homecraft business without the addition of any other ingredients, such as salt and sugar. Rice was soaked in water for two hours at room temperature and cooked in an electronic cooker (SR-056R, CUCKOO Inc., Republic of Korea) (Fig. 1). Density of rice product was determined by measuring volume change of water in a measuring cylinder immediately after a known amount of rice was added, although a delay of a few seconds was required to remove air bubbles in bagsulgi. Each grain of cooked rice was separated to avoid void volume because of adhesion between grain particles. Porcine pancreatic α-amylase (Type VII-A) was obtained from Sigma (St. Louis, MO, USA) and diluted to a protein concentration of 1 µg/mL in 0.1 M phosphate buffer (pH 6.9) with 0.006M sodium chloride. One hundred ppm of Thimerosal (Sigma, USA) was added in buffer solution to prohibit microbial contamination (5).

In vitro digestion of processed rice products

Each ten grams of garaeduk and bagsulgi was sliced into small pieces and ground in a food processor (Dongyang PCS, Republic of Korea) for 10 seconds. Cooked rice was pulverized with a spatula to simulate the same degree of mastication. A pretreated sample, equivalent to 0.5 grams of total carbohydrate, was put into a 100 mL Erlenmeyer flask with 50 mL of pH 6.9 phosphate buffer solution. Protein concentration of porcine pancreatic α-amylase in the buffer solution was 1 µg/mL. Enzymatic hydrolysis of each sample of processed rice product was carried out in a shaking water bath at 37°C. After a given reaction time, 1 mL of each sample solution was mixed with 9 mL of 50% ethanol followed by filtration (Whatman # 40, England). Reducing sugar was measured according to the Somogyi-Nelson method (8,9) using maltose (Sigma, USA) as a standard. The pretreated sample was placed in water with a 1 : 9 rice/water weight ratio and boiled until completely gelatinized. The method of Dubois et al. (10) was used to determine total carbohydrate content.

Cooked rice : Cleaning → Soaking (room temperature, 2 hour) → Cooking
Bagsulgi : Cleaning → Soaking (room temperature, 2 hour) → Milling → Steaming (20 min, 100°C) → Packaging
Garaeduk : Cleaning→ Soaking (room temperature, 2 hour) → Milling→ Steaming (25 min, 100°C) →Extrusion → Soaking in tap water for 10 min (repeat extrusion-soaking process three times) → Packaging

Fig. 1. Process flow for the preparation of rice products.

Experimental design for *in vivo* hydrolysis

The effect of rice products on postprandial glucose and insulin responses were examined in twelve healthy volunteers (6 male, 6 female). Anthropometric characteristics of the subjects are shown in Table 1. Mean age, body mass index (BMI) of the subjects were 23.2 ± 2.4 (mean ± SEM) yr, and 21.1 ± 1.6 kg/m^2, respectively.

Each subject was studied on three separate occasions, with at least two-week intervals in between. On the study days, subjects were offered cooked rice, bagsulgi or garaeduk containing 50 g of available carbohydrate with 400 mL of lukewarm water after an overnight fast. The product was consumed in 15 min. Venous samples were collected at 0 ~ 180 min. after eating, and centrifuged at 3,000 rpm for 20 min. Serum glucose was measured using a commercial kit based on the glucose oxidase method (11) (Sigma, St. Louis, MO, USA); and insulin was assayed using a radioimmunoassay (12) kit (Linco, St. Charles, MO, U.S.A.). Subjective satiety was measured before collection of each blood sample using a seven-point rating scale (13) anchored at -3 (very hungry) to +3 (very full). Serum glucose, insulin, and satiety were expressed as increments from baseline. Incremental areas under the response curves (AUC) were calculated using the trapezoidal rule with fasting levels as the baseline.

Statistical analysis

All data were described as mean ± standard error of mean (SEM) unless otherwise described. One-way analysis of variance (ANOVA) and the Turkey's test for multiple comparisons were used to determine statistical differences (α = 0.05).

RESULTS AND DISCUSSION

Physico-chemical properties of rice products

Fig. 1 illustrates the processing flow for making the rice products. Cooked rice was made by soaking in water for two hours and cooking with additional water to obtain a final moisture content of 66.0% (wt.). Bagsulgi, a steamed rice cake with hexahedral shape, was prepared by steaming rice flour. The steamed rice flour was extruded and soaked in water at room temperature to make garaeduk. The extrusion with subsequent soaking in water for making garaeduk was repeated three times in order to obtain the

Table 1. Characteristics of healthy subjects

Age (yr)	BMI (kg/m^2)	Body fat (%)	Waist/Hip ratio
23.2±2.4	21.1±1.6	20.2±1.9	0.8±0.02

typical texture. Garaeduk is typically shaped like a round stick.

Physico-chemical properties of the three rice products are shown in Table 2. Density of cooked rice was lowest among the processed rice products with no significant difference between the densities of garaeduck and bagsulgi. Cooked rice had the highest moisture content and bagsuli the lowest. As a consequence, bagsulgi had the highest amount of total carbohydrates per unit mass. Although there was no significant difference in density between bagsulgi and garaeduck, the extrusion process used in manufacturing it may impart some physical properties that distinguish it from bagsulgi. The longer steaming time and soaking in water, during garaeduk manufacturing, resulted in a higher moisture content of garaeduk than that of bagsulgi (Fig. 1).

In vitro digestion

In vitro hydrolysis of rice products with α-amylase revealed that the initial rate of hydrolysis was dependent on the preparation method (Fig. 2). Alterations of the physical form of rice starch as a consequence of processing method apparently affect the rate of enzymatic hydrolysis of processed rice products. Milling rice grain to make flour increases surface area of rice starch per mass. Therefore, enzymatic hydrolysis is faster for bagsulgi than for cooked rice, because the increased surface area allows for more sites of enzymatic action on substrate. However, garaeduk has a characteristic physical structure that causes the gelatinized starch molecule to be physically hard to access to the α-amylase enzyme molecule, thereby inhibiting hydrolysis. In other words, the initial rate of enzymatic hydrolysis of garaeduk is primordially dependent on particle size. Although the same procedure was used to homogenize garaeduk and bagsulgi, the enzymatic hydrolysis was slower for garaeduk due to the larger particle size, which was a consequence of densification during extrusion. Differences in the degree of enzymatic hydrolysis were eliminated when all three rice products were further hydrated and the reaction time lengthened. These results indicate that the hydrolysis rate of starch foods in humans can be controlled by, not only the structure of starch food itself, but also by the extent of mastication in mouth.

Table 2. Physico-chemical properties of rice products

	Cooked rice	Garaeduk	Bagsulgi
Density (g/mL)	1.11±0.01[1]	1.20±0.01	1.18±0.02
Moisture (wt. %)	66.0±2.2	47.5±0.1	43.1±0.2
Total carbohydrate (%)	29.2±2.0	45.1±0.1	48.9±0.1

[1] Mean±standard deviation.

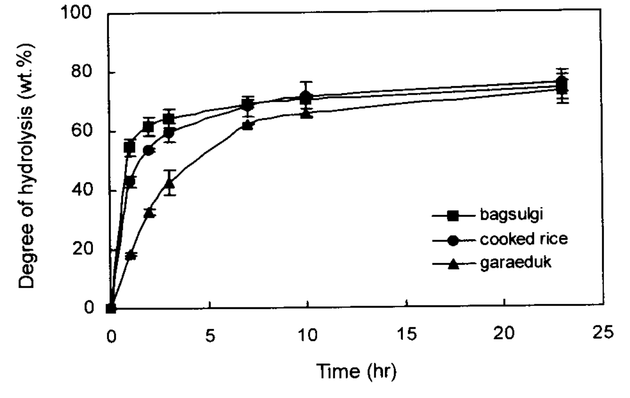

Fig. 2. *In vitro* hydrolysis of processed rice products with porcine pancreatic α-amylase.

Glucose and insulin level in blood and satiety after intake of processed rice products

Postprandial increases in serum glucose are shown in Fig. 3. Mean fasting serum glucose of the subjects was 84.9±8.6 mg/dL. Incremental serum glucose, after consumption of cooked rice, reached a peak at 30 min (41.8±2.2 mg/dL). This result is in agreement with the previous study of cooked rice (14). Incremental increases in serum glucose after consumption of bagsulgi (50.1±2.9 mg/dL) and garaeduk (38.3±3.2 mg/dL) also reached a peak at 30 min. Garaeduk had a significantly lower increase in incremental glucose levels compared with bagsulgi at 15 and 30 min ($p<0.05$). It is possible that the flattened postprandial glucose curve for garaeduk is due to a slower rate of digestion compared with bagsulgi, as shown in the *in vitro* study.

AUC (mg · min/dL) of the serum glucose response (Table 3) to bagsulgi tended to increase compared with that of cooked rice and significantly ($p<0.05$) increased compared to garaeduk. Holt and Miller (6) reported that incremental glucose AUCs of fine wheat flour bread significantly in-

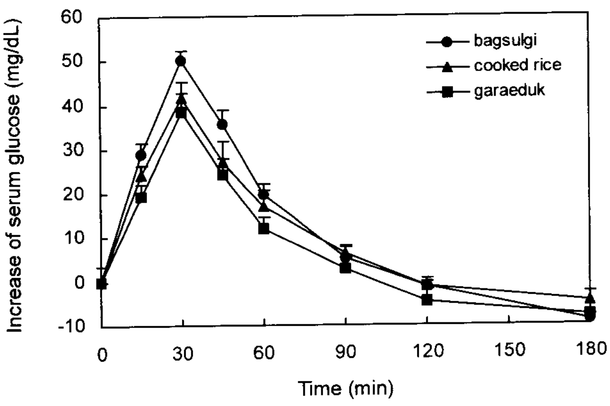

Fig. 3. Increase of serum glucose in normal subjects.

Table 3. AUC of serum glucose of normal subjects

	Cooked rice	Garaeduk	Bagsulgi
Mean	1980.6	1627.5	2407.4
SEM[1]	130.5	134.9	208.3
Significance	ab	a	b

[1] Standard error of mean.

creased compared with whole grain meal cooked at 230°C. However, in this study no significant difference was found between glucose AUC of garaeduk and bagsulgi made from rice flour and cooked whole grain rice. It seems that the effect of particle size on postprandial glucose is compromised by the physical integrity of rice product, which distinguishes it from bread. Since bread is baked with baking powder to obtain appropriate volume, significant increases in incremental glucose AUC of fine wheat flour bread compared with whole grain meal baked at the same temperature of 230°C is, in part, attributed to the difference in density of the two foods. Garaeduk consumption resulted in a significantly lower glucose AUC compared with bagsulgi. Although garaeduk is made from rice flour, the stronger and stickier structure, a consequence of extrusion during manufacturing, results in less susceptibility to mastication with slower digestion and decreased postprandial glucose responses.

Mean serum insulin levels were 9.88±0.83 μU/mL at time zero, and reached peak values at 30 min after consumption of the three rice products (Fig. 4). Postprandial insulin responses to garaeduk were significantly lower than those to bagsulgi at 30, 45, 60 min ($p<0.05$). AUC (μU · min/mL) of serum insulin of bagsulgi tended to be high compared with that of cooked rice (Table 4). Insulin AUC of garaeduk was significantly lower than that of bagsulgi ($p<0.05$). Foods with high glycemic indices are known to be one of the risk factors for Type II diabetes mellitus, because they increase postprandial blood insulin and insulin resistance (15). Long-term feeding of foods with lower glycemic indices decrease fasting glucose levels, secretion of insulin, and blood triglyceride levels (1,2). Since garaeduk significantly decreased postprandial insulin responses, compared with bagsulgi, garaeduk could be more beneficial in improving carbohydrate metabolism and insulin resistance.

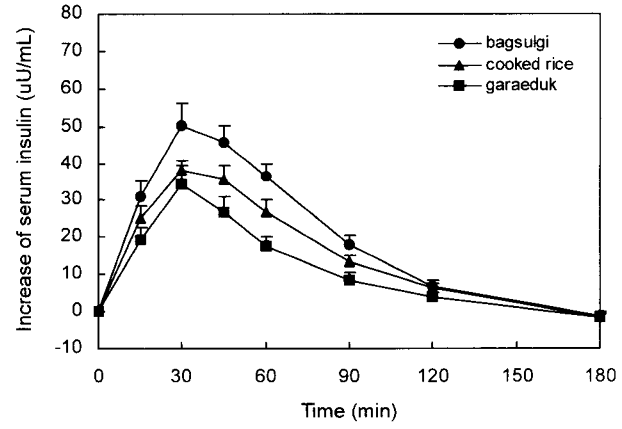

Fig. 4. Increase of serum insulin in normal subjects.

Table 4. AUC of serum insulin of normal subjects

	Cooked rice	Garaeduk	Bagsulgi
Mean	2759.7	2041.7	3581.8
SEM[1]	261.5	287.0	264.4
Significance	ab	a	b

[1] Standard error of mean.

The mean satiety score was −1.8±0.74 at time zero, and peak values occurred at 15 min (Fig. 5). There were no significant differences in incremental satiety of the three products at various time points. Satiety AUCs of cooked rice, bagsulgi and garaeduk were 250.0±19.3, 228.8±22.7 and 216.3±19.4, respectively. The mean differences among the products were not statistically significant. Therefore, garaeduk could be more effective in reducing postprandial increases in serum glucose and insulin without affecting satiety.

SUMMARY

Three differently processed rice foods, garaeduk, bagsulgi and cooked rice, were evaluated for their susceptibility to enzymatic hydrolysis, both *in vitro* and *in vivo*. No significant difference in density between garaeduk and bagsulgi was found. Moisture content of cooked rice, garaeduk and bagsulgi was 66.0, 47.5 and 43.1% (wt.), respectively. Food forms affected the initial rate of *in vitro* hydrolysis of processed rice foods with porcine pancreatic α-amylase. The structure of garaeduk, resulting from the pressure applied to steamed rice flour, caused it to be the least digestible *in vitro*, even though the same pre-treatment procedure was used to simulate mastication. The difference in physical forms of the rice products seemed to influence the particle size of each processed rice food after equivalent mastication, which, in turn, affected the specific surface area for enzymatic reaction. *In vivo* digestion of the three rice products was consistent with the results of *in vitro* hydrolysis with porcine pancreatic α-amylase. Postprandial serum glucose and insulin levels after consumption of the

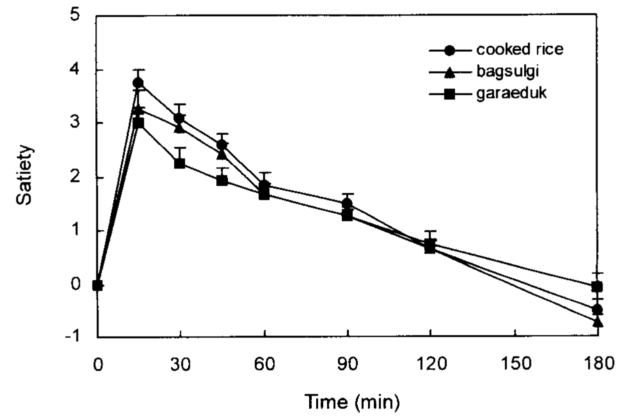

Fig. 5. Satiety in normal subjects.

rice products reached a peak at 30min. The least incremental responses for glucose (1627.5±134.9 mg · min/dL) and insulin (2041±287.0 μU · min/mL) were in the postprandial metabolism of garaeduk, which were significantly less than the glucose (2407.4±208.3 mg · min/dL) and insulin (3582 ±264.4 μU · min/mL) responses for bagsulgi. Satiety responses were not significantly different among the three rice products. Therefore, it can be concluded that garaeduk could be more beneficial in controlling postprandial hyperglycemia and hyperinsulinemia than bagsulgi.

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