Original Article

Postprandial glycemic response, sensory, and appetite evaluation of highland barley-multigrain rice versus white rice in healthy Chinese adults: A randomized crossover study

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Background and Objectives: Consumption of refined white rice, a staple food in most Asian countries, reportedly causes postprandial hyperglycemia and facilitates the development of diabetes. However, cereal grains with low glycemic indices may reduce postprandial glycemic response. We developed a highland barley-multigrain rice by combining traditional Chinese grains including, highland barley, brown rice, oats, corn grit, and buckwheat. This study aimed to evaluate the glycemic impact, sensory attributes, and appetite response of our highland barley-multigrain rice compared to white rice. **Methods and Study Design:** In this randomized crossover trial, ten healthy participants consumed highland barley-multigrain rice, white rice, and glucose, each containing 50 g of available carbohydrate under continuous glucose monitoring to compare postprandial glycemic responses over 180 min. The sensory and appetite ratings for the test foods were also evaluated. **Results:** The glucose response of highland barley-multigrain rice, based on the incremental area under the curve and peak glucose change levels, showed statistically lower values than white rice. The glycemic index at 120 min (42.9±4.4 vs.79.5±8.0, p <0.001) and 180 min (45.3±4.7 vs. 86.1±8.7, p <0.01) after the consumption of highland barley-multigrain rice was all significantly lower than those of regular white rice. Despite its relatively poor taste and overall preference rating, the highland barley-multigrain rice achieved a higher satiety score at 120 min after intake than white rice. **Conclusions:** As a low-glycemic index food, highland barley-multigrain rice could decrease postprandial glucose response and reduce hunger in healthy adults, indicating a potential role in improving glycemic control for patients with diabetes.

Key Words: highland barley, multigrain rice, glycemic index, postprandial glucose, appetite

INTRODUCTION

Diabetes has become one of the most prevalent and serious chronic diseases worldwide, leading to life-threatening, disabling, and costly complications, and significantly reducing life expectancy.[1] The estimated prevalence of diabetes among Chinese adults is approximately 12.4%. Moreover, the growing health burden underscores the urgent need for effective strategies to improve blood glucose control in individuals with diabetes.[2,3] Medical nutrition therapy is an integral part of diabetes treatment.[4] Experts have proposed a low-glycemic index (GI) diet as a useful means to effectively improve postprandial glycemic control due to its role of slow absorbed carbohydrates in reducing appetite.[5-7] The GI concept underscores the importance of carbohydrate quality over mere quantity in the dietary management of diabetes.

Rice is a starch-rich staple food in more than half of the world's population diet.[8] Currently it is predominately consumed in the form of highly refined white rice rather than unpolished brown rice, especially in the Asia Pacific region. Its consumption has been associated with an increased risk of developing type 2 diabetes, according to several studies, as it is a high GI food.[9-11] However, coarse grains such as buckwheat, oats, barley, corn, peas, and lentils that contain higher dietary fiber and also micro- and phytonutrients appear to be a healthier alternative to reduce the glycemic response and thus the risk of type 2 diabetes and other metabolic diseases.[12,13] The practice of mixing various grains with rice during cooking is fundamental in the traditional Chinese diet; there is also a wide array of whole grains that can be used for both mixed-grain rice and porridge. Previous studies have demonstrated the positive impact of adding coarse grains to a rice-based diet, including the reduction of fasting glucose levels, attenuation of postprandial glycemic responses, and moderation of insulinemic responses.[14,15]

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Highland barley (Qingke) is a particular cultivar of hull-less barley grown in the Qinghai-Tibet Plateau in China and is used as a food crop, brewing raw material, and an indispensable source of nutrition for Tibetans.[16] Given that the prevalence of diabetes among Tibetans is approximately 40% lower than the national average, researchers have increasingly focused on the potential metabolic protective effects of highland barley, which is rich in dietary fiber and soluble β-glucan.[16,17] Although it has a low GI value of 48, highland barley's less favorable taste and longer cooking time in comparison to rice and wheat hinder its widespread acceptance among patients with diabetes.[18]

The multigrain rice of "Mugi Gohan" in Japan, "Jabgogbab" in Korean have both been shown to have beneficial effects on postprandial blood glucose.[19,20] Consequently, we developed a multigrain rice product using highland barley, brown rice, oats, corn grit, and buckwheat and hypothesized that it may lead to a lower glycemic response. This study aims to systematically evaluate the glycemic impact, sensory, and appetite of highland barley-multigrain rice (HBMR) in comparison with white rice to provide empirical evidence that can guide clinical recommendations and dietary choices for better glycemic control.

METHODS

Ethics statements

The study was conducted in accordance with the guidelines of the Declaration of Helsinki, and all procedures involving human participants were approved by the Ethics Committee of Xinhua Hospital Affiliated to Shanghai Jiao Tong University School of Medicine (XHEC-C-2024-176-1) and registered in the Chinese Clinical Trial Registry as ChiCTR2400090208. All participants signed informed consent forms to ensure their voluntary participation in the study.

Study participants

Twelve healthy participants were recruited from Xinhua Hospital Affiliated to Shanghai Jiao Tong University School of Medicine through advertisement on social networks and by word of mouth. The inclusion criteria for participants were as follows: (1) aged between 18 and 50 years and having a normal BMI of between 18.5 and 25 kg/m^2; (2) not suffering from any metabolic diseases (such as diabetes or hypertension); (3) not taking any medications known to affect glucose tolerance and digestion (such as glucocorticoids, thyroid hormones, and thiazide diuretics); (4) no allergy history to the ingredients used in the study (glucose, highland barley, white rice, brown rice, oats, corn grit, and buckwheat); (5) capable of undergoing at least 8 h of fasting; and (6) not pregnant or breastfeeding.

Reference food and test foods

The Highland barley (Lantian Jingtu®, Xizang, China) was provided by Tibet Deqin Yangguang Manor Co., Ltd. White rice (Rong Xue®, Jiangsu, China) and dextrose monohydrate (Kingvita®, Fujian, China) were bought from the local Yuanhua supermarket. Brown rice, oats, corn grits, and buckwheat (Tianxi Lingxian®, Liaoning, China) were all purchased from Tmall Supermarket on the internet.

To determine the nutrients of test foods, total dietary fiber, β-glucan, and resistant starch contents of the grains were measured using the Megazyme assay kit (Megazyme, Ireland) of K-TDFR-100A, K-BGLU, and K-RSTCL, respectively. Data on total carbohydrate, protein, and fat were obtained from manufacturers. The content of available carbohydrate (ACHO) was calculated by total carbohydrate less dietary fiber. The energy (kcal) was calculated by multiplying protein, fat, dietary fiber, and ACHO contents by factors of 4, 9, 2 and 4, respectively.

The reference food was a glucose solution prepared by dissolving 55.0 g of dextrose monohydrate in 250 mL of water, yielding 50.0 g available carbohydrate. The highland barley-multigrain rice (HBMR) was evenly blended by five types of grain in specific proportions, including highland barley (25%), brown rice (20%), oats (20%), corn grits (20%), and buckwheat (15%). Each serving size for white rice (64.6 g) and HBMR (72.9 g) was adjusted to contain 50.0 g of carbohydrates before cooking as well. Before cooking, the highland barley-multigrain rice was soaked in 200 mL of water for 2 h to reduce cooking duration and enhance textural properties. On the day of the experiment, the test rice was washed thoroughly with ample water three times and drained. The rice was placed in an electric cooker (MB-WFS4029, Midea, China), and 100 mL of purified water was added and mixed appropriately. After the rice had been automatically cooked via the "Quick Cook" function, it was transferred to a plastic container on the warm setting and then consumed within 1 hour after cooking. The composition of reference food and test foods is shown in Table 1.

Study procedure

An open-label, randomized, cross-over design was adopted for this study in accordance with the guidelines of GI determination proposed by the Food and Agriculture Organization (FAO-1998) and the International Organization for Standardization (ISO-2010).[21,22] Figure 1 shows a schematic overview of the study sessions.

The participants were recommended to adhere to the following lifestyle and dietary habits throughout the study period: (1) avoid high-fiber and high-sugar foods for dinner (such as whole grains, legumes, celery, nuts, sugary drinks, desserts, honey, and fruits); (2) refrain from consuming any food or beverages (except water) starting from 8:00 p.m. every night to the next breakfast; and (3) avoid intense physical activity upon waking up each morning. Continuous glucose monitoring (CGM) (iPro™2 Professional CGM-Medtronic MiniMed, USA) was used to record glucose data (the participants were blinded to the records) at 5-min intervals for up to 5 days. The insertion was performed on day 0 of the study in the afternoon. During the study, the CGM sensor was calibrated against finger-stick blood glucose measurements four times a day before every meal and before sleeping using a glucometer (Contour TS® blood glucose meter, USA).

Table 1. Composition of the test foods per serving

Test foods	Weight (g)	Energy (kcal)	ACHO (g)	Protein (g)	Fat (g)
Glucose	55.0	200.0	50.0	0.0	0.0
White rice	64.6	217.9	50.0	3.4	0.5
Highland barley-multigrain rice	72.9	249.7	50.0	5.6	2.2
Highland barley	18.2	56.2	12.8	0.6	0.2
Brown rice	14.6	49.8	10.1	1.1	0.4
Oats	14.6	55.9	8.8	1.5	1.3
Corn grit	14.6	51.0	11.3	1.0	0.1
Buckwheat	10.9	36.9	6.9	1.4	0.3

Test foods	Dietary fiber (g)	β-glucan (g)	RS (g)
Glucose	0.0	0.0	0.0
White rice	0.2	0.0	2.1
Highland barley-multigrain rice	3.7	1.4	8.9
Highland barley	0.5	1.0	1.0
Brown rice	1.0	0.0	1.4
Oats	1.4	0.4	0.5
Corn grit	0.3	0.0	4.5
Buckwheat	0.5	0.0	1.5

ACHO: available carbohydrate; RS: resistant starch

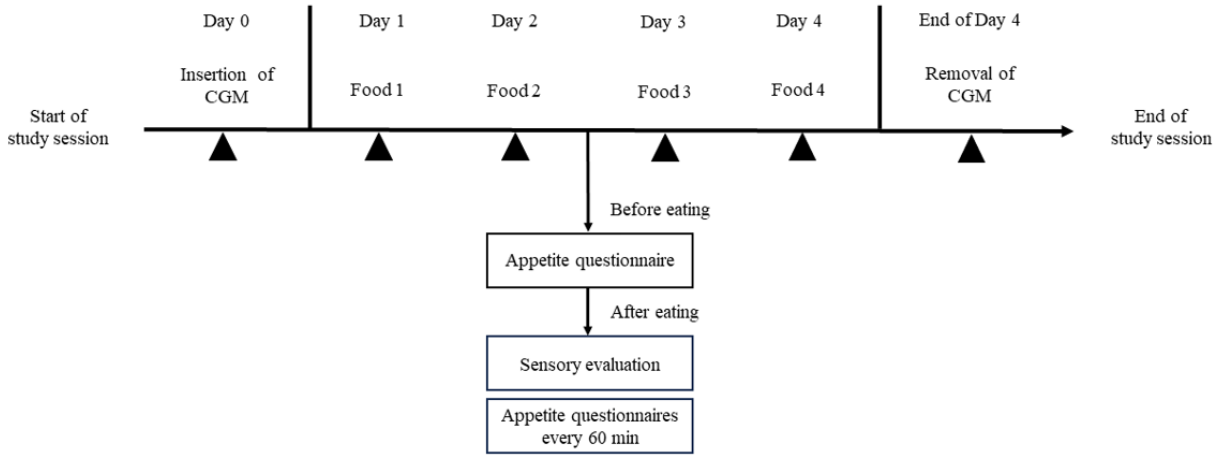

Figure 1. Study design and time flow of the 5-day trial. All participants consume the reference and test foods as breakfast while wearing the continuous glucose monitoring (CGM) device. The appetite questionnaires were complete before eating test foods and every 60 min after eating. Sensory evaluations of the test foods were conducted immediately after consumption

The order of consuming the reference and test meals was randomized using Microsoft Excel 2019's random function. Given the discernible differences in the appearance and texture of the meals, a double-blind methodology was not applicable. However, participants were not directly informed of the ingredients of the test meals. Each participant was required to consume the glucose meal twice and each test food once on separate days. On day 1 to day 4, the participants arrived at the department of endocrinology at Xinhua hospital at 8:00 am to consume the reference and test foods (along with 250 mL of water) daily for breakfast in a randomized sequence. All the participants were required to finish the meals within 5–10 min to minimize the effect of the gastric emptying rate. For the subsequent 3 h, the participants were required to only perform light activities (such as reading, watching movies, or typing) and were not allowed to consume any additional food or water. At the end of day 4, the CGMs were removed from the participants, and the data were collated and processed using an online software (Medtronic Diabetes CareLink iPro).

Concurrently, the participants completed sensory evaluations and appetite ratings of the test foods using a self-reported questionnaire. The sensory of test meals was evaluated across several attributes, including appearance, flavor, taste, texture properties, and overall preference. These attributes were measured using a 9-point structured scale, where 1 indicated "dislike extremely" and 9 indicated "like extremely."[23] Glossiness, color, and intactness were first evaluated as appearance characteristics of the cooked rice. The flavor was assessed through the purity and intensity of the fragrance, as well as the presence of unpleasant odors. We also investigated the taste of the rice meal, considering the fresh fragrance, sweetness, acidity, and bitterness when chewing. During the chewing stage, the texture properties of the test foods were evaluated by assessing several aspects, including springiness, chewiness, moistness, adhesiveness, and cohesiveness. Finally, the participants provided an overall preference rating based on the above evaluations.

The participants were asked to assess their hunger levels ("How hungry do you feel at this moment?") and

feeling of fullness ("How full does your stomach feel at this moment?") before the meal, immediately afterward, and every 60 min after consuming each meal over the subsequent 3 h. Measurements were obtained using a 100-mm visual analog scale (VAS) ranging from 0 ("not at all") to 100 ("extremely").[24] The appetite ratings of each participant at the subsequent time point values are shown as the difference from the baseline rating for each question.

Data processing and statistical analysis

The primary outcomes of the study were differences in the incremental area under the curve (iAUC) of postprandial glucose and GI between white rice and HBMR for the entire postprandial period of 120 and 180 min, respectively. Secondary outcomes included the time to maximum peak for glucose (Tmax) and maximum glucose change from baseline (ΔGlucose). Other outcomes included sensory scores and appetite ratings of the test foods. The iAUCs were geometrically calculated using the trapezoid rule, ignoring the area beneath the baseline glucose concentration.[21,25] The GI for the test food was calculated as the mean of individual ratios, using the following formula:

GI (%) = [iAUC of test food containing 50g ACHO /Mean iAUC of glucose containing 50g ACHO] × 100

All data are expressed as mean ± standard error of mean (SEM) values unless otherwise indicated. The distributions of the data collected were assessed through the Kolmogorov–Smirnov test as well as Q-Q plots. Differences in normally distributed outcomes were analyzed using a paired student's t-test, while non-normally distributed outcomes were analyzed using the Wilcoxon test. All statistical calculations were performed with SPSS

Table 2. Participants' characteristics (n=10)

Parameter	N (%) or mean ± SD
Male (%)	5 (50%)
Age (years)	32.1 ± 6.2
BMI (kg/m^2)	21.5 ± 2.4
SBP (mmHg)	109.8 ± 4.9
DBP (mmHg)	74.6 ± 5.2
Glu (mmol/l)	4.7 ± 0.4

SD: standard deviation; BMI: body mass index; SBP: systolic blood pressure, DBP: diastolic blood pressure, Glu: fasting blood glucose

Table 3. Postprandial glycemic characteristics of the test foods (n=10)†

Food	T_{max} (min)	$iAUC_{0\text{-}120min}$ (mmol/L min)	$iAUC_{0\text{-}180min}$ (mmol/L min)
Glucose	45.5 ± 1.9	175.1 ± 10.6	184.6 ± 10.9
WR	53.0 ± 4.8	138.4 ± 13.2	160.6 ± 23.1
HBMR	50.0 ± 5.1	74.1 ± 7.8***	82.9 ± 8.9**

Food	$GI_{0\text{-}120min}$	$GI_{0\text{-}180min}$	GI classification
Glucose	100 (Ref)	100 (Ref)	High
WR	79.5 ± 8.0	86.1 ± 8.7	High
HBMR	42.9 ± 4.4***	45.3 ± 4.7**	Low

Tmax: the time to postprandial glucose peak; iAUC: incremental area under the curve for glucose; GI: glycemic index; Ref: reference of GI; WR: white rice; HBMR: highland barley-multigrain rice. 0–120 min and 0–180 min represent the time after consuming the test foods. GI >70 indicates a high-GI food and GI<55 suggests a low-GI food.

** *p*-value < 0.01 after paired t test

*** *p*-value < 0.001 (HBMR compared to WR) after paired t test

†All values are mean ± SEM. iAUC was calculated using the trapezoid rule as area under the curve for glucose above baseline value.

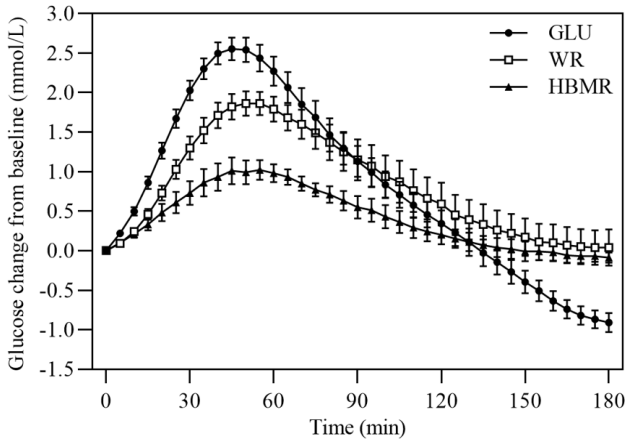

Figure 2. Glucose changes from baseline after consuming the three foods at each time point (n = 10). Values are shown as means, with their standard errors represented by vertical bars. HBMR shows a lower glycemic response than WR. GLU, glucose; WR, white rice; HBMR, highland barley-multigrain rice

(version 21; SPSS, Inc., Chicago, USA), and GraphPad Prism (version 8.0.2, GraphPad Software Inc., San Diego, USA) was used to generate the graphical elements. Statistical significance was set at $p < 0.05$.

RESULTS

Participant characteristics

Twelve participants were initially enrolled in the study and all met the inclusion criteria, with two subsequent withdrawals. One participant withdrew from the study due to an unforeseen allergy to the CGM sensor, and another withdrew for personal reasons. Finally, a total of 10 participants (5 male and 5 female participants, aged 26–48 years) completed the study and were included in the final analysis. The characteristics of the 10 participants are presented in Table 2.

Postprandial glycemic response

HBMR showed a lower postprandial glycemic response than white rice, with a more pronounced "gradual rise and gradual fall" characteristic (Figure 2). Despite the lack of statistical significance in the time to reach the glucose peak (Tmax) in Table 3, the mean change in glucose peak from baseline (ΔGlucose) for HBMR (1.25±0.10 mmol/L) was 39% lower than that for white rice (2.06±0.19 mmol/L, $p < 0.01$) as shown in Figure 3.

The mean iAUC of glucose and the GI of white rice and HBMR are shown in Table 3. The results showed that the iAUC0-120min of HBMR was 74.1±7.8 mmol/L·min, which was significantly lower than that of white rice (138.4±13.2 mmol/L·min, $p < 0.05$). This trend continued at the iAUC0-180min, with a value of 82.9 ± 8.9 mmol/L·min for HBMR ($p < 0.01$). In terms of GI, the GI0-120min of HBMR (42.9 ± 4.4) was determined to be statistically lower than that of white rice (79.5 ± 8.0, $p < 0.001$). Similarly, this significant difference in GI persisted, albeit slightly reduced, during the 0–180 min postprandial period (45.3±4.7 for HBMR vs. 86.1±8.7 for white rice, $p < 0.01$). Therefore, according to the GI classification rank (www.glycemicindex.com), HBMR can be classified as a low GI food.

Sensory evaluation

The sensory evaluation of HBMR and white rice is shown in Table 4. There was no significant difference in terms of appearance, flavor, and texture properties. However, HBMR received significantly lower scores in both taste (HBMR 5.5±0.4 vs. white rice 7.1±0.2, $p = 0.013$) and overall preference (HBMR 6.9±0.1 vs. white rice 6.3±0.2, $p = 0.031$) than white rice.

Appetitive response

Figure 4 shows the participants' ratings for hunger and fullness during the 3-h postprandial period. At 120 min after consumption, HBMR resulted in a lower feeling of hunger (HBMR (-43.0 ± 3.6 mm); white rice (-32.5 ± 3.0 mm)) and a greater sense of fullness (HBMR (40.3 ± 3.8 mm); white rice (31.9 ± 1.9 mm)) compared to white rice ($p < 0.05$ for both). Nevertheless, no significant differences in appetite evaluation were observed at other post-mealtime points.

DISCUSSION

This study aimed to determine whether HBMR differs from white rice in terms of postprandial glycemia, sensory attributes, and appetitive response when consumed in equal amounts of carbohydrates. Our findings indicate that HBMR elicits a significantly lower postprandial glycemic response and slower gastric emptying, aligning with our initial hypothesis; however, it has a relatively poor taste. To the best of our knowledge, this is the first study that focused on the potential benefits of multigrain rice enriched with highland barley on postprandial glucose regulation.

The reduced glycemic response observed with HBMR is consistent with the findings of previous studies that have reported the advantages of integrating whole grains into the daily diet to achieve enhanced glycemic control.[15,26-29] Zhu et al. replaced half of the rice in a given meal with whole-grain oats or pearled oats and found much lower GIs ranging from 59 to 70, whereas the GI of cooked rice was 84.[26] In our study, the standard GI value for white rice was 79.5, which is similar to the result reported by the aforementioned research, thereby corroborating the accuracy of our findings. In a randomized crossover study, the AUC of plasma glucose and insulin concentrations was reduced after consuming barley mixed with rice in a barley intake dose-dependent manner.[27] Due to the comprehensive and unique nutritional components discovered within a vast array of barley varieties, the highland barley was selected as the primary ingredient for our multigrain rice, which unsurprisingly led to stable postprandial glucose levels. Researchers have also found that the consumption of brown rice with legumes in place of white rice could help reduce 24-h glucose levels and insulin responses in overweight Asian individuals.[15] Furthermore, some recent studies have shown that incorporating corn fiber or sprouted buckwheat into a carbohydrate-based diet is also beneficial in controlling the postprandial glycemic response.[28,29] In this study, we developed a multigrain rice meal rich in various cereal grains, based on previous research findings and traditional Chinese dietary habits, and confirmed its low GI properties.

Low-GI diets have been associated with reduced risks of insulin resistance and metabolic syndrome in healthy adults. For instance, a meta-analysis of large cohorts (≥100,000 participants) demonstrated that low-GI diets are associated with reduced risks of diabetes, cardiovascular disease, diabetes-related cancers, and all-cause mortality, similar to those associated with increased consumption of fiber-rich foods and whole grains.[30] Furthermore, two randomized controlled trials, STOP-NIDDM and ACE, demonstrated that acarbose, an oral α-glucosidase inhibitor that effectively converts diets to a low GI dietary pattern, significantly reduced the incidence of diabetes, hypertension, cardiovascular disease, myocardial infarction, and stroke in individuals at risk of type 2 diabetes.[31-33] These findings also collectively suggest that low-GI diets may contribute to a reduced risk of metabolic disorders in healthy populations. Therefore, HBMR's low GI properties may serve as a preventive dietary strategy for maintaining metabolic health in at-risk populations.

Table 4. Sensory evaluation of test foods (n=10)†

Variable	White rice	Highland barely-multigrain rice	*p* value
Appearance	6.7 ± 0.3	5.9 ± 0.4	0.197
Flavor	6.5 ± 0.3	6.5 ± 0.4	0.678
Taste	7.1 ± 0.2	5.5 ± 0.4	0.013
Texture properties	6.0± 0.2	6.8 ± 0.4	0.094
Overall preference	6.9 ± 0.1	6.3 ± 0.2	0.031

† Data represent as mean ± SEM. p value was derived using paired t test
**p* <0.05.

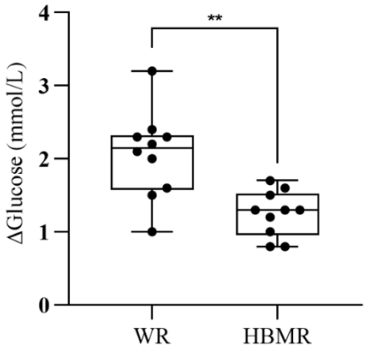

Figure 3. Box-and-Whisker plot of maximum glucose change from baseline after meals of WR and HBMR (n = 10). The two asterisks indicate statistical significance by paired t test with $p < 0.01$ between HBMR and WR. Vertical bars illustrate maximum and minimum values, the top and bottom of the box represent third quartile and first quartile values, respectively, and the line inside the box represents the median. Each point represents a single value of ΔGlucose for each participant. ΔGlucose, maximum value of glucose change from baseline; WR, white rice; HBMR, highland barley-multigrain rice

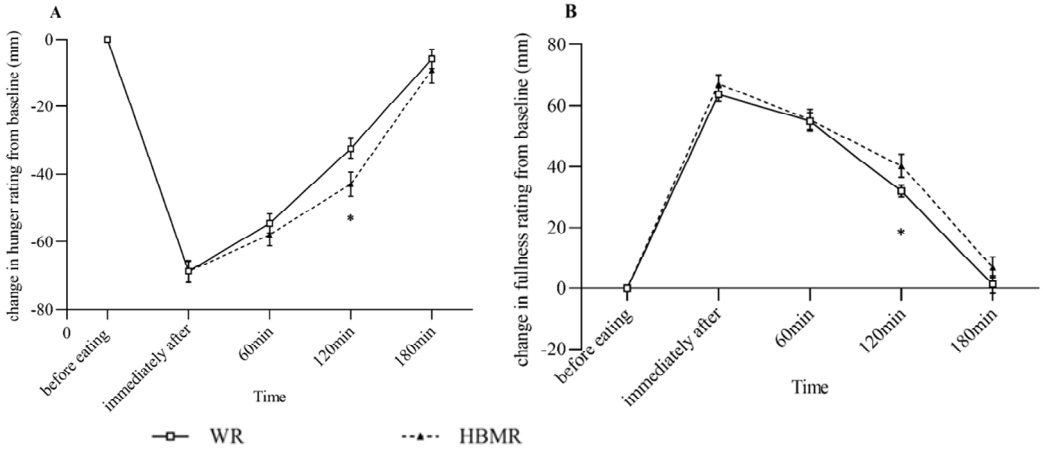

Figure 4. Change in appetite rating using a visual analog scale (n = 10). (A) Hunger rating; (B) Fullness rating. Values were adjusted to the baseline ratings per participant for each test food and expressed as mean ± SEMs. Significant differences (**p* <0.05) in hunger and fullness ratings between test foods were both found at 120 min after eating (paired t-test). WR, white rice; HBMR, highland barley-multigrain rice

Several factors affect the glycemic response and satisfactory sense of carbohydrate-rich food, which is the case for dietary fiber, particularly β-glucan. Meal enrichment of soluble dietary fiber has been shown to increase chyme viscosity and decrease postprandial blood glucose, fasting blood glucose, and insulin concentration.[34] The HBMR boasts a total dietary fiber content that reaches up to 5.1%, significantly surpassing the 0.3% found in traditional white rice. Previous studies have shown that cereal β-glucans are naturally present in oats and barley, with a content of about 4.5%, while rye and wheat have lower concentrations, with a β-glucan content reaching up to 2.5% in their bran.[35] Highland barley is extremely rich in β-glucan, with levels higher than those of the aforementioned cereals, as some varieties have been shown to have β-glucan content of up to 8.62%.[36] Our multigrain rice is enriched with β-glucans, predominantly sourced from highland barley and oats, which contain approximately 5.4% and 2.9% β-glucans, respectively. The positive effects of β-glucans on blood glucose are well established. The European Food Safety Authority (EFSA) recommends adding at least 8 g of oats β-glucan into the daily diet for every 60 g of available carbohydrates to achieve the goal of lowering blood glucose levels. When chewed in the mouth, β-glucans absorb water and swell, forming a gel-like solution with extremely high viscosity and elasticity. This not only greatly slows down the gastrointestinal emptying speed of starchy foods but also encapsulates

starch to form a special network structure that hinders the binding of α-glucosidase, α-amylase, and invertase, while also significantly reducing the absorption speed of glucose from the small intestine; therefore, β-glucans can effectively play a role in delaying the rise of postprandial glycemic levels.[35,37]

Starch is the primary component of cereal grains and the main contributor to postprandial glucose increases after a meal. Based on in vitro amylolysis and digestion rates, starches are generally classified into three types: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS).[38] Unlike RDS and SDS, which are hydrolyzed in the small intestine to produce glucose, RS passes through the small intestine intact and is fermented similarly to dietary fiber in the large intestine by intestinal microorganisms. A review that included six studies summarized the acute effect following a single intake of RS in addition to available carbohydrate in healthy individuals: five studies showed that RS could improve glycemia by lowering glucose iAUC0–120min, and three studies revealed that the glucose peak was relatively lower after the consumption of RS.[39] Therefore, consuming RS may be an effective short-term approach for reducing postprandial glycemic response. Most studies that discuss the benefits of RS were performed using commercially obtained ingredients containing high-amylose maize starch, which is isolated from a special hybrid of corn that is naturally high in amylose content.[40] It is worth noticing that the RS content of HBMR in our study was as high as 12.2%, and corn grit, one of its constituent components, boasts an impressive RS content of 30.7%. Consequently, we hypothesized that the high RS content would enhance fullness and ensure a mitigating effect on glycemic response.

Our findings may also be attributed to the unique textural characteristics of these cereal grains, such as their hardness and chewiness. The chewy texture could cause slower eating rates and increase the release of appetite-suppressing gut peptides such as glucagon-like peptide 1 and peptide YY, which in turn upregulate glucose-stimulated insulin secretion.[41] An epidemiological study in a Japanese population found that slow eating and more thorough chewing can lead to reduced glycemic responses, lower glycated hemoglobin, and decreased risk of diabetes.[42] Based on these insights, we hypothesize that the under-mastication of HBMR may slow ingestion, decrease starch digestibility, and promote the secretion of satiety-related hormones.

The flavor of rice is closely related to the sustainability of rice consumption in daily life. Foods with a low GI can be instrumental in managing blood glucose levels; however, their dietary adherence can falter if their palatability is lacking. Though the HBMR tested in our study does not exhibit sensory differences in appearance, flavor, and texture properties when compared to white rice, there was a recognized need for further enhancement in taste to ensure consumer satisfaction and dietary compliance.

A key strength of our research is the application of the CGM system for the assessment of the GI. The Medtronic iPro™2 device can generate a glucose concentration reading every 5 min, allowing us to collect 36 glucose measurements within the 180 min following the consumption of the test food. Consequently, we are confident that the postprandial blood glucose response curve generated by the CGM more accurately represents the actual physiological conditions within the participants. Furthermore, the discomfort experienced by subjects was markedly diminished compared to the traditional fingerstick blood sampling, further enhancing participant compliance in the study.

The present study had some limitations. First, it was conducted in a relatively small group of healthy Chinese adults, which may limit the generalizability of our results. Further studies that include participants with pre-diabetes, diabetes, and obesity are encouraged. Second, the study's short-term duration restricted our ability to infer the long-term impacts on glycemic regulation or weight management strategies. Additionally, as this was a pilot study, insulinemic responses and gastrointestinal hormones, which would have provided more explanations of underlying mechanisms, were not explored. Finally, this study did not explore advanced processing methods (e.g., enzymatic treatment, extrusion, or fermentation) that may have enhanced the sensory properties of HBMR while preserving its glycemic benefits. Future research could investigate whether such techniques could mitigate the lower taste scores of HBMR without compromising its low-GI characteristics.

Conclusion

In conclusion, the HBMR is a low-GI food that could achieve a significantly lower postprandial glycemic response and slightly higher fullness than white rice. Although its taste requires further improvement, the potential health benefits of HBMR make it a promising candidate for inclusion in dietary recommendations for individuals with diabetes.

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CONFLICT OF INTEREST AND FUNDING DISCLOSURES

The authors declare no conflict of interest.

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REFERENCES

1. Heald AH, Stedman M, Davies M, Davies M, Livingston M, Alshames R, Lunt M, Rayman G and Gadsby R. Estimating life years lost to diabetes: outcomes from analysis of National Diabetes Audit and Office of National Statistics data. Cardiovasc Endocrinol Metab. 2020; 9: 183-5. doi: 10.1097/XCE.0000000000000210
2. Wang L, Peng W, Zhao Z, Zhang M;Shi Z;Song Z, et al. Prevalence and Treatment of Diabetes in China, 2013-2018. JAMA. 2021;326: 2498-506. doi: 10.1001/jama.2021.22208
3. Sun H, Saeedi P, Karuranga S, Pinkepank M, Ogurtsova K, Duncan BB, et al. IDF Diabetes Atlas: Global, regional and country-level diabetes prevalence estimates for 2021 and projections for 2045. Diabetes Res Clin Pract. 2022;183:109119. doi: 10.1016/j.diabres.2021.109119.
4. Evert AB, Dennison M, Gardner CD, Garvey WT, Lau K, MacLeod J, et al. Nutrition Therapy for Adults With

Diabetes or Prediabetes: A Consensus Report. Diabetes Care. 2019;42:731-54. doi: 10.2337/dci19-0014.
5. Thomas DE, Elliott EJ. The use of low-glycaemic index diets in diabetes control. Br J Nutr. 2010;104:797-802. doi: 10.1017/S0007114510001534.
6. Gerontiti E, Shalit A, Stefanaki K, Kazakou P, Karagiannakis DS, Peppa M, Psaltopoulou T, Paschou SA. The role of low glycemic index and load diets in medical nutrition therapy for type 2 diabetes: an update. Hormones (Athens). 2024. doi: 10.1007/s42000-024-00566-7.
7. Ojo O, Ojo OO, Adebowale F, Wang XH. The Effect of Dietary Glycaemic Index on Glycaemia in Patients with Type 2 Diabetes: A Systematic Review and Meta-Analysis of Randomized Controlled Trials. Nutrients. 2018;10:373. doi: 10.3390/nu10030373.
8. Fukagawa NK, Ziska LH. Rice: Importance for Global Nutrition. J Nutr Sci Vitaminol (Tokyo). 2019;65:S2-S3. doi: 10.3177/jnsv.65.S2.
9. Hu EA, Pan A, Malik V, Sun Q. White rice consumption and risk of type 2 diabetes: meta-analysis and systematic review. BMJ. 2012;344:e1454. doi: 10.1136/bmj.e1454.
10. Sun Q, Spiegelman D, van Dam RM, Holmes MD, Malik VS, Willett WC, Hu FB. White rice, brown rice, and risk of type 2 diabetes in US men and women. Arch Intern Med. 2010;170:961-9. doi: 10.1001/archinternmed.2010.109.
11. Aune D, Norat T, Romundstad P, Vatten LJ. Whole grain and refined grain consumption and the risk of type 2 diabetes: a systematic review and dose-response meta-analysis of cohort studies. Eur J Epidemiol. 2013;28:845-58. doi: 10.1007/s10654-013-9852-5.
12. Venn BJ, Mann JI. Cereal grains, legumes and diabetes. Eur J Clin Nutr. 2004;58:1443-61. doi: 10.1038/sj.ejcn.1601995.
13. Hu Y, Ding M, Sampson L, Willett WC, Manson JE, Wang M, Rosner B, Hu FB, Sun Q. Intake of whole grain foods and risk of type 2 diabetes: results from three prospective cohort studies. BMJ. 2020;370:m2206. doi: 10.1136/bmj.m2206.
14. Winham DM, Hutchins AM, Thompson SV. Glycemic Response to Black Beans and Chickpeas as Part of a Rice Meal: A Randomized Cross-Over Trial. Nutrients. 2017;9:1095. doi: 10.3390/nu9101095.
15. Mohan V, Spiegelman D, Sudha V, Gayathri R, Hong B, Praseena K, et al. Effect of brown rice, white rice, and brown rice with legumes on blood glucose and insulin responses in overweight Asian Indians: a randomized controlled trial. Diabetes Technol Ther. 2014;16:317-25. doi: 10.1089/dia.2013.0259.
16. Obadi M, Sun J, Xu B. Highland barley: Chemical composition, bioactive compounds, health effects, and applications. Food Res Int. 2021;140:110065. doi: 10.1016/j.foodres.2020.110065.
17. Peng W, Li K, Yan AF, Shi Z, Zhang J, Cheskin LJ, Hussain A, Wang Y. Prevalence, Management, and Associated Factors of Obesity, Hypertension, and Diabetes in Tibetan Population Compared with China Overall. Int J Environ Res Public Health. 2022;19:8787. doi: 10.3390/ijerph19148787.
18. Atkinson FS, Brand-Miller JC, Foster-Powell K, Buyken AE, Goletzke J. International tables of glycemic index and glycemic load values 2021: a systematic review. Am J Clin Nutr. 2021;114:1625-32. doi: 10.1093/ajcn/nqab233.
19. Matsuoka T, Yamaji A, Kurosawa C, Shinohara M, Takayama I, Nakagomi H, Izumi K, Ichikawa Y, Hariya N, Mochizuki K. Co-ingestion of traditional Japanese barley mixed rice (Mugi gohan) with yam paste in healthy Japanese adults decreases postprandial glucose and insulin secretion in a randomized crossover trial. Asia Pac J Clin Nutr. 2023;32:40-7. doi: 10.6133/apjcn.202303_32(1).0007.
20. Kim MJ, Hur HJ, Jang DJ, Kim MS, Park S, Yang HJ. Inverse association of a traditional Korean diet composed of a multigrain rice-containing meal with fruits and nuts with metabolic syndrome risk: The KoGES. Front Nutr. 2022;9:1051637. doi: 10.3389/fnut.2022.1051637.
21. Institution BS. Food products. Determination of the glycaemic index (GI) and recommendation for food classification. ISO International Standard (ISO). 2010.
22. Nutrition Division F. Carbohydrates in human nutrition. Fao Food & Nutrition Paper. 1998;66.
23. Maitre, I. Rapid Sensory Profiling Techniques. 2015:485-508. doi: 10.1533/9781782422587.4.485.
24. Flint A, Raben A, Blundell JE, Astrup A. Reproducibility, power and validity of visual analogue scales in assessment of appetite sensations in single test meal studies. Int J Obes Relat Metab Disord. 2000; 24: 38-48. doi:10.1038/sj.ijo.0801083
25. Chlup R, Jelenová D, Kudlová P, Chlupová K, Bartek J, Zapletalová J, Langová K, Chlupová L. Continuous glucose monitoring -- a novel approach to the determination of the glycaemic index of foods (DEGIF 1) -- determination of the glycaemic index of foods by means of the CGMS. Exp Clin Endocrinol Diabetes. 2006;114:68-74. doi: 10.1055/s-2006-923806.
26. Zhu R, Fan Z, Li G, Wu Y, Zhao W, Ye T, Wang L. A comparison between whole grain and pearled oats: acute postprandial glycaemic responses and in vitro carbohydrate digestion in healthy subjects. Eur J Nutr. 2020;59:2345-55. doi: 10.1007/s00394-019-02083-5.
27. Sakuma M, Yamanaka-Okumura H, Naniwa Y, Matsumoto D, Tsunematsu M, Yamamoto H, Taketani Y, Takeda E. Dose-dependent effects of barley cooked with white rice on postprandial glucose and desacyl ghrelin levels. J Clin Biochem Nutr. 2009;44:151-9. doi: 10.3164/jcbn.08-232.
28. Tan W, Chia P, Ponnalagu S, Karnik K, Henry CJ. The Role of Soluble Corn Fiber on Glycemic and Insulin Response. Nutrients. 2020;12:961. doi: 10.3390/nu12040961.
29. Kang L, Luo J, Su Z, Zhou L, Xie Q, Li G. Effect of Sprouted Buckwheat on Glycemic Index and Quality of Reconstituted Rice. Foods. 2024;13:1148. doi: 10.3390/foods13081148.
30. Jenkins D, Willett WC, Yusuf S, Hu FB, Glenn AJ, Liu S, et al. Association of glycaemic index and glycaemic load with type 2 diabetes, cardiovascular disease, cancer, and all-cause mortality: a meta-analysis of mega cohorts of more than 100 000 participants. Lancet Diabetes Endocrinol. 2024;12:107-18. doi: 10.1016/S2213-8587(23)00344-3.
31. Augustin L, Kendall C, Jenkins D, Willett WC, Astrup A, Barclay AW, et al. Glycemic index, glycemic load and glycemic response: An International Scientific Consensus Summit from the International Carbohydrate Quality Consortium (ICQC). Nutr Metab Cardiovasc Dis. 2015;25:795-815. doi: 10.1016/j.numecd.2015.05.005.
32. Chiasson JL, Josse RG, Gomis R, Hanefeld M, Karasik A, Laakso M, STOP-NIDDM Trail Research Group. Acarbose for prevention of type 2 diabetes mellitus: the STOP-NIDDM randomised trial. Lancet. 2002;359:2072-7. doi: 10.1016/S0140-6736(02)08905-5.
33. Holman RR, Coleman RL, Chan J, Chiasson JL, Feng H, Ge J, et al. Effects of acarbose on cardiovascular and diabetes outcomes in patients with coronary heart disease and impaired glucose tolerance (ACE): a randomised, double-blind, placebo-controlled trial. Lancet Diabetes Endocrinol. 2017;5:877-86. doi: 10.1016/S2213-8587(17)30309-1.
34. Giuntini EB, Sardá F, de Menezes EW. The Effects of Soluble Dietary Fibers on Glycemic Response: An

Overview and Futures Perspectives. Foods. 2022;11:3934. doi: 10.3390/foods11233934.
35. Henrion M, Francey C, Lê KA, Lamothe L. Cereal B-Glucans: The Impact of Processing and How It Affects Physiological Responses. Nutrients. 2019;11:1729. doi: 10.3390/nu11081729.
36. Dang B, Zhang WG, Zhang J, Yang XJ, Xu HD. Evaluation of Nutritional Components, Phenolic Composition, and Antioxidant Capacity of Highland Barley with Different Grain Colors on the Qinghai Tibet Plateau. Foods. 2022;11:2025. doi: 10.3390/foods11142025.
37. Battilana P, Ornstein K, Minehira K, Schwarz JM, Acheson K, Schneiter P, Burri J, Jéquier E, Tappy L. Mechanisms of action of beta-glucan in postprandial glucose metabolism in healthy men. Eur J Clin Nutr. 2001;55:327-33. doi: 10.1038/sj.ejcn.1601160.
38. Englyst HN, Kingman SM, Cummings JH. Classification and measurement of nutritionally important starch fractions. Eur J Clin Nutr. 1992;46 Suppl 2:S33-50.
39. Tsitsou S, Athanasaki C, Dimitriadis G, Papakonstantinou E. Acute Effects of Dietary Fiber in Starchy Foods on Glycemic and Insulinemic Responses: A Systematic Review of Randomized Controlled Crossover Trials. Nutrients. 2023;15:2383. doi: 10.3390/nu15102383.
40. Lockyer S, Nugent AP. Health effects of resistant starch. NUTRITION BULLETIN. 2017;42:10-41. doi: 10.1111/nbu.12244.
41. Shah M, Crisp K, Adams-Huet B, Dart L, Bouza B, Franklin B, Phillips M. The effect of eating speed at breakfast on appetite hormone responses and daily food consumption. J Investig Med. 2015;63:22-8. doi: 10.1097/JIM.0000000000000119.
42. Yamazaki T, Yamori M, Asai K, Nakano-Araki I, Yamaguchi A, Takahashi K, et al. Mastication and risk for diabetes in a Japanese population: a cross-sectional study. PLoS One. 2013;8:e64113. doi: 10.1371/journal.pone.0064113.