Rheological properties of brown and white rice during *in vivo* digestion in pigs

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**ABSTRACT**

The effects of processing on food digestion have not been clearly established, particularly how initial food properties affect gastric digestion *in vivo*. Rheological properties of gastric contents were used as a measure of overall digestion, as they have been correlated with the gastric emptying rate of a meal. The objective of this study was to determine the effect of rice processing on the rheological properties of gastric digesta in pigs over a two hour time period in the proximal and distal regions of the stomach. Sampling of digesta was performed 20, 60, or 120 min after consumption of a brown or white rice meal. Viscous and viscoelastic properties of the digesta were measured. Flow behaviour was modelled using nonlinear regression techniques in Matlab. Rice gastric digesta was non-Newtonian and behaved as a Herschel-Bulkley fluid, with yield stress values ranging from 109.3-3.9 Pa for white rice and 56.6-0 Pa for brown rice. The consistency index ($K_H$) was greater in brown rice (826-428 Pa·s$^n$) than in white rice (461-40 Pa·s$^n$), and decreased with increasing digestion time. The viscoelastic properties showed that the rice digesta behaved as a gel, with $G'$ (42288-1911 Pa) greater than $G''$ (6307-360 Pa) over the entire frequency range tested. Viscous and viscoelastic properties were affected by rice type and digestion time. White rice showed a greater variation between rheological properties of the proximal and the distal regions of the stomach compared to brown rice, suggesting that mixing was altered by meal composition. Digesta rheological properties play an important role in determining the gastric emptying rate of a meal, which has been correlated to satiety and blood glucose response. Knowledge of the effect of processing on digesta properties can enable the optimization of rice processing to design food products with selected digestive characteristics.

**Keywords:** gastric digestion; rice; rheology; pigs

**INTRODUCTION**

Approximately 650 million tons of rice are grown annually worldwide [1], and it is a staple food in the diets of many cultures. Starch makes up about 90% of the dry matter content of rice, so it is the most important contribution of rice to the human diet [2]. Rice digestion has been studied *in vitro*, in rats, and in humans with the objective of investigating how rice prepared with various cooking methods or different amylose:amylopectin ratios produce different glycemic responses and rates of starch hydrolysis. These studies have shown that both cooking method and amylose:amylopectin ratio in starch play a role in rice digestion [3, 4]. However, these previous studies have only studied the intestinal contents or the blood glucose response after consumption of a rice meal. Since the flow of digesta into the small intestines and the glucose entering the blood is governed by gastric emptying and the breakdown of food in the stomach, this will play an important role in the overall digestion process. Rice digestion has been studied in pigs with the objective of determining how the diet properties affect intestinal digestibility and pig preference of various cereals [5, 6], however, stomach contents were not thoroughly analyzed. In the current study, we examine the stomach contents of pigs after consumption of a rice meal in order to determine the breakdown of rice particles during the first 2 hours of digestion, as the gastric digestion step of the digestive process has been overlooked in many of the current studies.

Rice digestion has been studied in humans by examining changes in blood glucose after a meal. This measurement is used in many nutrition studies, as it is a non-invasive measurement that gives a good idea of the rate of digestion of a food. After food particles are broken down enough to leave the stomach, they move through the small intestine. It has been demonstrated that all ingested glucose will be absorbed in the small intestine, with the majority being absorbed in the proximal half of the small intestine [7]. This rate of glucose absorption into the blood has been used as an indicator to the rate of food digestion. To easily compare the...
glucose response for many different food products, the glycemic index (GI) was developed. The glycemic index is expressed as the area under the glucose response curve after consumption of a test meal containing 50 g total carbohydrates. This area is normalized with the glucose response after consumption of either a white bread meal or a glucose meal, so tests from many subjects can be easily compared [8]. The glycemic index is widely accepted as a measure of the rate of digestion, particularly for foods high in carbohydrates. Studies have shown that the GI will depend on food structure, starch type, moisture content, among other factors, and international tables of GI values have been established for >150 different food products worldwide [9]. GI has been shown to be a good predictor of gastric emptying rate, and has shown an inverse correlation with the gastric emptying half-time (i.e. low GI value, long gastric emptying half-time) [10]. Studies that have investigated the GI of rice have shown that both the processing [11] and the specific starch composition [3] will affect the GI, hypothesized to be due to changes in gastric emptying of the rice.

In order to study the gastric digestion of a rice meal, examining both the gastric emptying and the particle breakdown, the properties of the digesta must be quantified. Rheological properties of gastric contents play a role in the breakdown of solid particles, with the forces experienced by the particles in the stomach being driven by the gastric viscosity [12]. Studies have shown that gastric viscosity, and not initial meal viscosity is the best predictor of the rate of gastric emptying of a meal [13], and that the gastric viscosity is heavily influenced by the amount and size of particles present [14]. The previous work suggests that the rheological properties of gastric contents play an important role in not only the particle breakdown, but also in the gastric emptying rate of the meal, and may be useful to quantify the properties of gastric digesta.

The current study examines the changes in gastric digesta rheological properties in brown and white rice over a 2 hour digestion period in both the proximal and distal regions of the stomach. We hypothesized that observed differences in GI of more and less processed foods could be observed in the case of brown and white rice. Rheological properties were measured to give an idea of the overall state of the gastric digesta, and also because they will change over time due to the breakdown and emptying of food particles as well as the addition of gastric secretions. This information can be used to develop a link between the initial food properties and how foods break down during the gastric digestion process. This knowledge can enable food processors to develop innovative processes and products that have selected digestive characteristics.

MATERIALS & METHODS

All procedures were approved by the Animal Ethics Committee at Massey University, New Zealand. Thirty six entire male pigs (approximately 20 kg bodyweight) were housed individually in metabolism crates at an ambient room temperature of 23 ± 1°C. Water was available ad libitum throughout the trial except for the final day. Animals were randomly assigned to an experimental diet such that there were six animals per treatment (diet x sampling time). Diets consisted of rice (brown or white) with vitamin and mineral mix (2.5 g kg⁻¹), whey protein (141.2 g kg⁻¹), and soybean oil (100 g kg⁻¹) added after cooking. All diets met the nutritional requirements for growing pigs as prescribed by the National Research Council for all nutrients except protein. The daily ration for each pig was 10% of their metabolic bodyweight (bodyweight³⁰.⁷⁵) and was given as two equal sized meals fed at 0900 h and 1400 h. The pigs were fed the rice diet for a 7 day acclimatization period. On day 8 (the penultimate day of the study), the pigs were given unrestricted access to a 25% dextrose water solution.

Each meal for each pig was prepared separately using either short grain white rice or long grain brown rice. The rice:water ratio was 1:1.25 (v/v) for white rice and 1:1.75 (v/v) for brown rice. Rice was cooked in a Kambrook rice cooker, with total cooking time being 25 min for white rice and 45 min for brown rice. After cooking, both rice types remained in the rice cooker on the “warm” function for 5 min. After removal from the rice cooker, the rice meals were cooled to 40°C, and the vitamin and mineral mix, whey protein and soybean oil were added and mixed thoroughly before feeding.

On the final day of the study, water was removed 2 hours prior to the pigs receiving their final test meal to ensure the stomach and upper GI tract was empty. The pigs were fed their daily rice ration (without the vitamin mineral mix, whey protein, or soyabean oil) but containing titanium dioxide (3g/kg cooked rice). At 0, 60, or 120 min after consumption of the final meal, the pigs were sedated with Xylazine (2.2 mg/kg) and Zolazepam/Tiletamine (4.4 mg/kg) by intramuscular injection and euthanized by an intravenous injection of a lethal dose of pentobarbitone while under anaesthesia. The total digestion time was calculated from when the pig finished eating the final meal until the recorded time of death. The pigs were dissected and the stomachs carefully removed, the outside washed with deionised water and carefully dried with absorbent paper. The stomachs were dissected and samples taken from the fundus/body (proximal) region and the antral
The pH of each sample was measured before the sample was neutralized to pH 7 with NaOH and frozen at -20°C. Prior to analysis the samples were thawed to room temperature maintained at 55°C.

Rheological measurements were taken using a Paar-Physica rheometer MCR301 (Anton Paar GmbH, Austria) with a plate-plate geometry consisting of a 40 mm PP40 parallel plate with a 5 mm gap. The measurements were taken at 37°C, with a 2 minute equilibration period before beginning any test. The flow behaviour was measured by testing shear rates in the range of 0.001 – 1.5 1/sec. The viscoelastic properties were measured by varying the frequency from 0.1-10 Hz at a constant strain of 0.5%. Herschel-Bulkley flow parameters were determined using the “lsqcurvefit” function in Matlab.

**RESULTS & DISCUSSION**

Both the flow properties and viscoelastic properties show consistent trends in brown and white rice over the digestion period. Brown rice has a greater viscosity and larger storage and loss modules, at all time points when compared to white rice. Both brown and white rice decrease in viscosity and viscoelastic parameters with increasing digestion time, as the particles are being broken down and gastric secretions are being mixed with the rice particles. The differences between brown and white rice increase over time; after only 20 minutes of digestion, brown and white rice have more similar rheological properties than after 120 minutes of digestion. When comparing the proximal and distal regions of the stomach, in both brown and white rice, there is a large difference in rheological properties between the proximal and distal region at 20 minutes of digestion, however, this difference disappears at the longer digestion times (Figures 1 & 2).

![Figure 1](image-url)  
*Figure 1. Shear stress vs. shear rate (n = 6) at 20 min digestion time for brown and white rice. Symbols represent observed values and lines represent modelled values.*
The flow behaviour curves show that the rice digesta behaved as a Herschel-Bulkley fluid, having a yield stress then following shear-thinning behaviour (Figures 1 & 2). From the Herschel-Bulkley parameter values (Table 1), it can be seen that the yield stress in the proximal region decreases with increasing digestion time for both brown and white rice (37.7-0.0 and 109.3 – 3.9, respectively).

The viscoelastic properties showed that the rice digesta behaved as a gel, with $G'$ (42288-1911 Pa) greater than $G''$ (6307-360 Pa) over the entire frequency range tested. The white rice storage modulus ($G'$) decreased with digestion time, with the proximal region greater than the distal region for all digestion times (Figure 3). Brown rice storage modulus values did not significantly change either over digestion time or stomach region (Figure 4).

**Table 1. Herschel-Bulkley parameters.**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Yield Stress (Pa)</th>
<th>K (Pa·s^n)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Rice Proximal</td>
<td>20</td>
<td>109.3</td>
<td>461</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>26.2</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>3.9</td>
<td>147</td>
</tr>
<tr>
<td>White Rice Distal</td>
<td>20</td>
<td>27.2</td>
<td>312</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>16.6</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>13.2</td>
<td>40</td>
</tr>
<tr>
<td>Brown Rice Proximal</td>
<td>20</td>
<td>37.7</td>
<td>826</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>41.6</td>
<td>428</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>0.0</td>
<td>584</td>
</tr>
<tr>
<td>Brown Rice Distal</td>
<td>20</td>
<td>53.3</td>
<td>652</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>56.6</td>
<td>456</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>49.1</td>
<td>551</td>
</tr>
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</table>
The differences seen between the rheological properties of brown and white rice are due to the initial properties of the rice, demonstrating that food material properties influence the overall breakdown of the foods during the digestion process. Studies have shown that soluble dietary fibre (SDF) content can increase the rheological properties of digesta and slow gastric emptying time [15, 16]. Brown rice has greater SDF content than white rice, which could have contributed to the increase in rheological properties. Water content also plays a major role in determining the rheological properties of digesta; white rice had higher moisture content than brown rice, which could have contributed to the lower rheological properties of white rice.

Previous studies have shown that particle size distribution, in particular, large particles, play a major role in determining the viscosity and viscoelastic properties of intestinal and cecal contents [14, 17, 18]. The greater viscosity seen in brown rice could have been partially caused by the presence of more, larger particles than white rice. The presence of mucins and other gastric secretions could also affect the rheological properties of the digesta. Brown rice and white rice both had an equal amount of initial gastric sections, yet the moisture content increase for white rice digesta was much greater than that for brown rice. This suggests that brown rice may have had a greater amount of other gastric secretions, such as mucins, which could have also...
increased the viscosity. This is also supported by the observation that there were more mucus-like substances observed in the stomachs of the pigs that had consumed brown rice.

CONCLUSION

The results from this study show that initial physical properties of food greatly affect their breakdown during digestion. The physiological response (amount of gastric secretion and gastric emptying) to the rice types of varying structures is also different, suggesting that the gastric digestion process is adapted according to the specific food consumed. Mixing has shown to play an important role, as the properties observed were not only dependent on the rice type and digestion time, but also on whether the digesta was taken from the proximal or distal stomach. This supports the hypothesis that the stomach contents are not evenly mixed and that the proximal and distal regions of the stomach play unique roles in the digestion process.

REFERENCES