A Human Gastric Simulator (HGS) to Study Food Digestion in Human Stomach

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Abstract: The objective of this study was to develop an in vitro stomach model, the Human Gastric Simulator (HGS), for studying gastric digestion of foods. The HGS is designed in such a way as to simulate the continuous peristaltic movement of stomach walls, with similar amplitude and frequency of contraction forces as reported in vivo. The HGS mainly consists of a latex vessel, simulating the stomach chamber, and a series of rollers secured on belts that are driven by motor and pulleys to create a continuous contraction of the latex wall. It also incorporates gastric secretion, emptying systems, and temperature control that enable accurate simulation of dynamic digestion process for detailed investigation of the changes in the physical chemical properties of ingested foods. The simulated gastric contraction force demonstrates a similar pattern as in vivo stomach forces. The precise control of gastric secretion and emptying and the adjustable mechanical forces in the HGS provide a useful tool to study transformation of food constituents under simulated physiological conditions.

Keywords: gastric emptying, gastric secretion, Human Gastric Simulator (HGS), in vitro model, peristaltic movement, size distribution, stomach contraction

Practical Application: HGS could be used to study changes in the physical and chemical properties of gastric contents, and transformation of food constituents that occur during simulated digestion, and the influence of physiological conditions including acid and enzyme secretion and contraction forces on disintegration kinetics of foods and nutrient release.

Introduction

The stomach is the major compartment for food disintegration in a human body, where both biochemical reactions and mechanical size reduction occur contributing to breakdown of chewed solid food into small size. Mastication or chewing is the 1st step in the food digestion process that reduces food particle size and mixes food particulates with saliva to create a bolus. The food bolus is conveyed to the stomach through the esophagus by the process of peristalsis. Peristalsis is an advancing contractile wave of the walls of a flexible conduit that forces the contents of the conduit forward. In the stomach, peristaltic contractions are initiated by tonic contractions on the upper surface of the stomach, and continue down to the pyloric valve (Urbain and others 1990; Schulze 2006). The peristaltic waves travel toward the pylorus in a sequential manner, with 2 to 3 peristaltic contractions proceeding at any time. The contraction frequency is approximately 3 cycles per minute. The propagation velocity averages 2.5 mm per second, and increases from the proximal to distal stomach. Each contraction takes about 1 min to advance from the fundus to the pylorus (Schulze 2006). The peristaltic contraction mixes foods with gastric juice and propels this mixture to the bottom of the stomach, also called the “antrum.” The antrum is where foods receive the most intense squeezing and crushing forces, causing efficient food breakdown. Liquids and small particles (< 1 to 2 mm) flow continuously from the stomach through the pyloric opening into the duodenum, while the indigestible particles greater in size are squirted back into the stomach, by an action called retropulsion. Repeated propulsion, grinding, and retropulsion reduce the size of food particles and convert the mixture into emulsion-like digesta. The stomach contractions, particularly antral contraction, play a significant role in the disintegration of solids. Researchers have measured the contraction forces present in the stomach, and reported values ranging between 0.2 N and 1.89 N, depending on the fasting or fed state and the approaches used to measure the forces (Kamba and others 2000; Marciani and others 2001). This mechanical destruction combined with chemical reactions change the food mixture into a softer consistency in a suspension form that is called “chyme” and expelled into the duodenum.

In vitro gastrointestinal tract models have been developed in recent years and they are finding use in the food, nutrition, and medical research due to their advantages in saving time and cost, and certain levels of reproducibility in comparison with in vivo studies (Kong and Singh 2008a, 2008b). Many in vitro approaches mimic gastric digestion by simply mixing food and gastric fluid using a shaking bath (Muir and O’Dea 1992), magnetic stirrer (De Boever and others 2001), or head-over-heels mixer (Oomen and others 2003). Obviously, these approaches oversimplify the mixing patterns, and cannot reproduce the fluid mechanics and the mechanical forces that foods encounter in the stomach resulting from contractions of the stomach wall.

Some of the more sophisticated dynamic gastrointestinal models include the dynamic gastric model (DGM) invented by the
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Inst. of Food Research, U.K., and TNO’s gastrointestinal model (TIM), developed at TNO Nutrition and Food Research (Zeist, The Netherlands). The DGM uses a fixed outer cylinder with a movable inner cylinder to crush foods in between, creating mechanical breakdown of foods (Wickham and Faulks 2008). The types of forces applied on foods in the DGM are different from the forces that foods receive during peristaltic movement. TIM attempts to simulate peristaltic movements by using glass jackets with a flexible inner wall where water is pumped into the space between the inner and outer walls with variable water pressure, causing the inner wall to expand and contract (Yoo and Chen 2006). This contraction is different from the actual stomach contractions due to the lack of creating antral contraction, where foods receive the maximum mechanical force. The absence of antral contraction also means that retropropulsion cannot be created, altering the overall flow patterns in TIM from that found in vivo. The shape of the glass jackets is also different from a real stomach that has a reduced cross-sectional area at the lower end. These differences suggest that the in vitro systems available to date are unable to create realistic gastric environment for food breakdown. Accordingly, it is believed that there remains a need for a system that incorporates more accurate peristaltic movements to model the digestion of foods and pharmaceuticals.

This paper presents a new dynamic stomach model, Human Gastric Simulator (HGS) that has been designed in a way to produce continuous peristaltic movement of stomach wall similar to in vivo observations. By combining realistic peristaltic waves, this device can provide a more accurate simulation of stomach wall movement, producing mechanical forces acting on foods that are comparable to the forces measured in vivo, thus providing better simulation of food digestion. This model also incorporates gastric secretion and emptying to simulate the dynamic process of gastric digestion. The performance of HGS was evaluated by digesting rice and apple slices in HGS and analyzing the digesta properties, including particle size distribution, solids content, and pH profiles.

Model Development

The main components of the HGS are a latex lining chamber to mimic stomach, mechanical driving system composed of 12 rollers secured on belts pushing the stomach walls driven by a motor assembly, gastric secretion and emptying systems, and temperature control (Figure 1). The entire system rests on a large aluminum base plate. Detailed description of each part is as follows:

Stomach chamber

The round cylindrical stomach vessel is made of latex rubber due to its durability and elasticity. The main latex body has a dia of 102 mm (4 inches) and a depth of 280 mm (11 inches), and it has a collective volume of 5.7 L (1.5 gallons). The latex vessel is held by a stainless steel clamp at the top that is supported by 4 legs extending from the clamp to the base plate, so that the stomach vessel stays straight up with a 330 mm (13 inches) height. Each leg was welded to the base with 90° separating each one horizontally (Figure 1). The top end of the vessel was left open by wrapping around a stainless steel ring for accommodating food materials, and the ring has a dia of 152 mm (6 inches) and a width of 102 mm (4 inches). The bottom end of the latex vessel is tapered with an angle of 75 degrees to reduce the dia to 25 mm (1 inch). A plastic tubing with internal dia 3.2 mm (1/8 inch) connects the vessel bottom to a peristaltic pump (Masterflex Pump Controller 7553-50/7090-42 Pump, Cole-Parmer, Chicago, Ill., U.S.A.) for emptying digesta from the vessel.

During digestion trials, a thin polyester mesh bag with net pore size of 1.5 mm is placed inside the latex vessel, covering the inner wall of the latex. This bag allows small particulates of < 1 to 2 mm to pass through the mesh for emptying and retains large particulates for further breakdown, thus simulating a sieving effect of pylorus. The mesh bag can be easily taken out for washing and removing any remaining foods after the trial that allows a detailed analysis of the food residue remaining in the stomach.

Figure 1–HGS. (1) Motor; (2) latex lining; (3) mesh bag; (4) secretion tubing; (5) roller; (6) belt; (7) light bulb for temperature control; (8) plastic foam insulation.
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The rollers and the drive system
A mechanical driving device consisting of 12 rollers, 4 belts, driving shafts, and pulley system were installed to create peristaltic contractions on 4 sides of the latex stomach vessel (Figure 1 and 2). The custom-made rollers consist of 2 wide Teflon wheels of 12.7-mm dia (1/2 inch) and 9-mm thickness, and 11 mm apart from each other. The 2 wheels are secured on an aluminum rod, whose other end has female thread that is engaged with a male threaded screw with 2-mm dia and 15-mm length. The rollers are screwed on 4 timing belts that are 610-mm (24 inch) long and 9.5-mm (3/8 inch) wide, distributed along the 4 equally spaced sides of the stomach. Each belt has 3 rollers that are spaced equally apart (Figure 2). The belts are driven by a motor taken from a 115 V Stir-Pak Heavy-Duty Mixer head (model R-50002-10, Cole-Parmer) with a Stir-Pak controller (model R-50002-02, Cole-Parmer), with adjustable speed ranging from 2 to 180 rpm. The driver is set to create 3 contractions per minute on the latex vessel, to simulate the actual stomach contraction frequency of 3 cycles per minute (Schulze 2006). When the motor is running, the drive-shafts rotate, driving the belts through a set of pulleys to move, carrying the rollers to move down the latex wall, thus creating contraction on 4 equally spaced sides of the vessel. To avoid possible clash between the rollers on the neighboring belts when they approach the bottom of the latex vessel, the 4 rollers are placed on 2 different elevations with 1 pair of opposite rollers placed 30 mm higher relative to the other (Figure 3). The contraction force can be changed by changing the distance between the opposite rollers through adjusting the screw engagement depth inside the aluminum rod.

The detail of the drive-shafts and pulley system are shown in Figure 2 and 3. The drive-shafts are 12.7-mm (1/2 inch) dia brass rods that drive a 9.5-mm (3/8 inch) pulley, and in turn drive the timing belt. Four low-carbon steel plates are used to hold the 4 pulley systems in place. Bearings are mounted onto each plate in order to stabilize the rotating shafts. Power is transmitted from the 1st drive shaft to the other 3 via right angle drives (Figure 2). Right angle drives consist of 2 bevel gears coupled together at a 90° angle. This allows power to be transmitted from one shaft to another shaft (Figure 3).

Gastric secretion
A variable flow mini peristaltic pump (Model 3385, VWR, Scientific, Rochester, N.Y., U.S.A.) delivers simulated gastric juice into the simulated stomach chamber through a 6.4-mm (1/4 inch) ID plastic pipe splitting into 5 polyethylene tubing (I.D. 0.86 mm). A control valve is used to adjust the flow rate for the tubing (Figure 1 and 2). Inside the latex chamber, the 5 tubing are placed in between the mesh bag and the latex lining, with the end tips placed at different elevations, approximately 10 to 15 mm height from the bottom, to allow a uniform distribution of secretion of gastric juice. The flow rate of gastric secretion can be adjusted between 0.03 and 8.2 mL/min.

Temperature control
The entire assembly is housed in an insulated plastic foam chamber. Two 60 W light bulbs are installed to maintain the temperature at 37 °C and a thermostat (Model T675A 1516, Honeywell, Honeywell Inc., Minneapolis, Minn., U.S.A.) is used to turn on/off the bulbs automatically. A mini fan is installed to distribute the air in the chamber to achieve a uniform temperature. It may take 30 min to increase the temperature from room temperature to 37 °C. A portable air heater may also be used to speed up the initial heating when necessary.

Material and Methods

Materials
Rice (Mahatma, extra long grain enriched rice) and California grown “Fuji” apple were purchased from a local grocery store. Simulated gastric juice was prepared by dissolving pepsin (1 g), gastric mucin (1.5 g), and NaCl (8.775 g) in 1 L distilled water.
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with pH of 1.3 adjusted using 6 N HCl. Simulated saliva was prepared by dissolving gastric mucin (1 g), α-amylase (2 g), NaCl (0.117 g), KCl (0.149 g), and NaHCO₃ (2.1 g), in 1 L distilled water. All chemicals were purchased from Sigma-Aldrich, Inc. (St. Louis, Mo., U.S.A.).

Measurement of contraction force

The mechanical force generated by the HGS was measured by using a thick-walled rubber bulb (dia 22 m) attached to a hand-held digital manometer (Dwyer, series 475 Mark III) (Figure 4). The bulb was placed in the bottom of the HGS filled with water, corresponding to the antrum of the human stomach. When the HGS was in operation, the moving wall compressed the balloon to generate a pressure that was recorded. The relationship between pressure and force on the balloon was determined by using a texture analyzer TA-XT2 (Texture Technologies Corp., Scarsdale, NY/ Stable Micro Systems, Godalming, Surrey, U.K.) with a cylindrical flat end probe (4 cm dia) to compress the bulb. The pressure was recorded using the manometer and the applied force was measured by the texture analyzer simultaneously. A linear relationship between pressure and force was obtained (Figure 5). The pressure readings recorded from HGS contraction were then converted to force using the linear equation.

Batch digestion of apple and rice in HGS as compared with shaking bath

Apple and rice representing a fruit and a starchy food, respectively, were digested comparing HGS and shaking bath method.
that is often used to simulate gastric movement (Muir and O’Dea 1992). A batch process was employed in HGS without gastric juice secretion and emptying. Apples were cut into cubes with sizes ranging from 6.3 to 9.5 mm. Apple cubes (100 g) were mixed with 20 mL simulated saliva (Gavião and others 2004), held for 2 min, and then 70 mL simulated gastric juice was added. The mixture was then digested in the HGS for 2 h. The same amount of pretreated apple samples were digested in a beaker placed in a shaking bath (shaking frequency: 120 rpm) at 37 °C for 2 h. Then the mixtures from both HGS and shaking bath were separated into different size categories using wet sieving method, with 6.3, 4, and 2.8 mm sieves. Moisture was determined using a hot air oven set at 105 °C until constant weight was obtained. The amount of dry mass in each size category was calculated.

Rice was prepared using a rice cooker (RC3406, Black & Decker, Md., U.S.A.). 150 g rice and 30 mL simulated saliva were manually mixed in a beaker for 30 s (Watanabe and Dawes 1988). The mixture was allowed to stand for 2 min, and then 120 mL gastric juice was added. The mixture was digested in HGS for 2 h. As a comparison, same amount of pretreated rice samples were digested in the shaking bath for 2 h operated at 120 rpm. After digestion, the digesta from both HGS and shaking bath was passed through a 0.8-mm sieve. The digesta retained on the sieve were dried out and the weight was measured. The filtrate that passed through the sieve was tested for particle size distribution using a Laser diffraction particle size analyzer (LS-100Q, Beckman Coulter, Fullerton, Calif., U.S.A. particle size range: 0.375 to 948.2 μm).

Digestion of rice in HGS as affected by contraction forces

50 mL of simulated gastric juice was loaded into HGS before adding rice to mimic a condition where the stomach holds a certain amount of gastric juice during fasting (Camilleri 2006). 200 g cooked rice was mixed with 40 mL simulated saliva, allowed to stand for 2 min, and then transferred into the HGS. The gastric juice secretion started immediately after the mixture was introduced into the HGS, and continued at 2.5 mL/min (Hoebler and others 2002). The emptying was regulated by using the peristaltic pump. For every 15 min, 45 mL of digesta fluid was collected in plastic tubes, corresponding to an emptying rate of 3 mL/min. For each sample, pH and solids content were determined. The solids content was measured using a portable refractometer 300003 (Sper Scientific Ltd., Scottsdale, Ariz., U.S.A.). The readings of refractometer were calibrated against the solids concentration obtained by using the hot air oven. pH was measured using an Accumet Research AR20 pH/Conductivity meter (Fisher Scientific, Pittsburgh, Pa., U.S.A.). The tubes containing samples were placed in an ice bath while the trial was running. After 3 h of trial time, the HGS was stopped. The collected samples and the digesta remaining in the HGS were pooled together for size distribution analysis using wet sieving method, comprising of 3 sieves with pore size 1.2, 2.36, and 3.35 mm, respectively. The amount of dry solids on each sieve was determined by using hot air oven. The size distribution was calculated in terms of the weight of dry mass.

To evaluate how mechanical forces affect digestion, the rice digestion trials were conducted with 2 different contraction forces. The contraction force was adjusted by changing the gap between the 2 opposite rollers, with the minimum gap (that is, the distance between 2 opposite rollers when they approach the bottom section) of 6 mm and 12 mm, respectively. The change in particle size distribution of digested rice under the 2 different force conditions was compared.

Statistical analysis

A significance test was conducted using analysis of variance (ANOVA) in the GLM procedure of the SAS System to analyze the effect of HGS on size distribution of foods. Differences between group means were analyzed by Duncan’s multiple-range test. Statistical significance was set at a probability level of 0.05. The coefficient of variation (CV) was calculated as a percent of the standard deviation to the mean value (SD/mean × 100) and was used to evaluate the repeatability of the stomach model.

Results and Discussion

Model performance

An important design criterion for the HGS was to reliably generate continuous peristaltic waves in the simulated stomach wall, and to ensure that food in the model receive similar amplitude and frequency of contraction forces as observed in vivo. This function was provided by using a series of rollers to compress the latex stomach wall driven by a motor and a controller that creates undulating waves within the stomach. The rollers move in a simultaneous fashion to create the “ring-shaped” peristaltic motion that accurately represent the real peristaltic motion in a stomach as reported in the literature (Urban and others 1990; Schwizer and others 2006). By accurately simulating the peristaltic wave motion, HGS is able to replicate the motility of the stomach more completely than some of the other in vitro models reported in the literature, such as the “DGM” and “TIM” models.

In a human stomach, the overall gastric motility in the proximal stomach compartment is minor; stronger contractions occur in the distal part mainly in the antrum, with higher depth and amplitudes (Schwizer and others 2006). Therefore, it is expected that the food in the antrum part of the in vivo model should receive the maximum contraction force, and experience similar movements as in a human stomach, including propulsion, retropulsion, and grinding. In HGS, the vessel shape is tapered at the bottom to mimic the actual stomach shape that has a reduced size in the antrum. The rollers and belts are assembled in a way to start indenting the latex at the upper top part of the stomach, two-thirds of the total height. The contraction ring shrinks as the rollers roll down the chamber, thus increasing the amplitude of the waves.
and creating a stronger churning force. When the rollers approach the bottom of the tapered latex vessel, the gap between the 2 opposite rollers narrows down to a minimum, creating a maximum mechanical force on foods simulating the “antral contraction.” Meanwhile, retropulsion is produced that can be clearly observed where the digesta is pushed upward by the enclosed contraction ring. The digesta then falls to the bottom region due to the effect of the gravity. During the process, foods receive repeated squeezing, mixing, and grinding that cause gradual disintegration of solid foods.

In a stomach, the pylorus partially opens causing a “sieving effect” to allow liquids and small particles (<1 cm to 2 mm) to flow continuously from the stomach into the duodenum, while the indigestible particles greater in size than the pyloric opening are retropelled and retained in the stomach. This function is achieved in HGS by placing a thin polyethylene mesh net with 1.5-mm pore size in the latex chamber (Figure 1 and 2). This mesh net is proven to be effective in selectively passing small size particulates (mostly < 1.5 mm) and retain big size particulates. In a human stomach, the mechanism regulating emptying is complicated, which involves antral contractions as well as pyloric contractions. The antroploroduodenal contractions acting as a peristaltic pump are a major factor in the regulation of gastric emptying of solid meals. The spatial and temporal parameters of gastropyloroduodenal contractions, such as frequency, amplitude, duration are all important (Haba and Sarna 1993). Further improvements are being planned to incorporate these functions in order for HGS to simulate more precisely the gastric emptying process.

Contraction force

In vivo studies have found that stomach forces vary depending on gender, age, or health of trial subjects (Vassallo and others 1992; Marciani and others 2001). Urbain and others (1990) observed that the amplitude of the contractions decreased in the course of gastric emptying of a physiological test meal. An advantage of HGS is its ability to generate different amplitude and frequency of mechanical forces by adjusting the gap distance between the 2 opposite rollers and the rotational speed of the motor. These features make HGS able to mimic various mechanical forces acting on foods in a human stomach that helps to study food digestion under different physiological conditions.

The maximum antral force in HGS, measured by using the 22-mm dia balloon connected to a digital manometer (Figure 4), was 2.56 ± 0.45 N and 3.39 ± 0.95 N for each contraction, when the minimum gap between 2 opposite rollers was set at 12 mm and 6 mm, respectively. To compare with in vivo results reported in literature, the force value was normalized by the cross-sectional area of the balloon, in the units of mechanical stress, determined as 6738 and 8922 N/m², respectively. Researchers in medical and nutrition area have measured the mechanical forces presented in a human stomach using different approaches, and reported various force values. For example, Marciani and others (2001) reported mechanical force of 0.65 N applied on agar gel beads (dia 12.7 mm) present in the stomach, while Kamba and others (2000) reported 1.89 N for a press-coated tablet with 7 mm in length and 4 mm in width. These values correspond to an area-normalized mechanical stress of 5134 to 67292 N/m².

These results suggest that the force value measured in the HGS is in a reasonable range of forces presented in a human stomach. Figure 6 compares the force profiles generated by HGS when the minimum gap of opposite rollers equals 12 mm, and in vivo force profiles reported by Vassallo and others (1992), who used an axial force transducer to measure the forces along the longitudinal axis of the distal stomach (Vassallo and others 1992). Although Figure 6B only reflects the axial forces presented in the antrum, it provides a good reference for the antral force pattern on the ingested foods such as the shape and frequency. A good agreement can be seen between the pattern of in vivo (Figure 6A) and in vivo forces (Figure 6B), indicating that the system can be used to generate a similar force pattern on foods as observed in vivo.

Comparison between HGS and shaking bath method in food disintegration

Experiments were conducted to compare the use of HGS and a shaking bath in digesting apple and rice, respectively. In this experiment, the amount of saliva and gastric juice added into foods are determined based on the weight of apple and rice, and the flow rate of saliva and gastric juice obtained from literature data involving in vivo measurements (Watanabe and Dawes 1988; Gavião and others 2004), as well as in vitro tests (Hoelker and others 2002; Oomen and others 2003). Figure 7 compares the particle size of apple after digestion in HGS and the shaking bath. It can be seen that HGS significantly reduced the amount of large size particulates while increased the amount of small size particulates. The digesta from the shaking bath comprised of particulates with 61% in the size range d > 6.3 mm and 20% in the range d < 2.8 mm, compared with 16% and 69% for the digesta from the HGS in the 2 size ranges, respectively. This result indicates that with the help of the mechanical force created by simulated peristaltic movement, HGS is more effective in disintegrating food than the shaking bath in which little mechanical force is involved.

Similar effect was observed in rice digested in the HGS and the shaking bath. It was observed that most rice kernels were intact after digestion in the shaking bath, while in the HGS, rice kernels

Figure 6–Profile of contraction force: (A) in vitro force created in the bottom part of HGS simulating antral force in human stomach; (B) in vivo antral axial force profile (Vassallo and others 1992).
were broken into fine particulates and an emulsion-like digesta was produced. When the digesta from both approaches were filtered using the 0.8-mm sieve, 86% of the of the dry solids in the mixture from shaking bath were retained on the sieve, compared to 48% from the HGS digestion, indicating much higher breakdown efficiency in the HGS. In order to further investigate the size difference generated in HGS and shaking bath method, the filtrate of 0.8-mm sieve were analyzed using a Laser diffraction particle size analyzer (LS-100Q). Figure 8 compares the particle size distribution of the filtrate comparing HGS with shaking bath. It can be seen that in the shaking bath, after sieving, the particle size was in the range of 0 to 300 μm, and almost no particles exist outside this range. However, for HGS digesta, the size distribution covers the entire range of the size spectrum. This result indicates that HGS caused an effective breakdown of rice kernel resulting in a wider range of particle size, due to the effect of crushing and squeezing effect generated by the simulated contractions. However, in the shaking bath, the particle breakdown is not significant; solid leaching may be the main mechanism for the solid release leading to a major portion of particles found in the narrow range of smaller size (Kong and Singh 2009b). As particle size has profound influence in the release of nutrients, the significant difference in the particle size distribution implies that the release kinetics of nutrients may be strongly affected by the in vitro method employed, especially the amount of mechanical force delivered by the system. These results indicated that by combining the physical forces resulting from peristaltic contraction, together with the enzymatic and acidic reactions, HGS significantly improves efficiency of food disintegration as compared with the shaking bath method, and results in a possibly more realistic particle size distribution. These features should help the study of accessibility of nutrients embedded in a food matrix.

Figure 7 also indicates a good repeatability of the model. For 3 replicate trials, CV of the data of particle size distribution, calculated as the ratio of the standard deviation to the arithmetic mean, are generally within 7%.

Using HGS for rice digestion with continuous gastric secretion and emptying

The release of nutrients from solid food depends on the physical and chemical characteristics of foods, as well as dynamic physiological events including pH, gastric emptying, and enzymatic secretion. Experiment was conducted using rice as model food to investigate how controlled gastric secretion and emptying, as well as variable mechanical forces in HGS affect in vitro digestion of rice, as reflected by the reduction of particle size, rate of solids release, and change of pH in the digesta. In this experiment, constant rate of gastric secretion and emptying was employed to simplify the digestion process. A trial time of 3 h was selected because most solid foods are emptied within 3 to 5 h (Oomen and others 2003). During the 3-h trial, the total addition of gastric juice was 450 mL, and the total volume of emptied digesta was 540 mL. The volume of mixture in the HGS was initially approximately 290 mL, and decreased to 200 mL at the end of the trial.

As one of the major component in gastric juice, acid plays a critical role in assisting food digestion by hydrolyzing carbohydrates and activating enzymes (Kong and Singh 2009a). Creating a similar profile of pH evolution in the in vitro model as in the human stomach is critical for an effective simulation of the digestion process. The pH profile in HGS following ingestion of rice is shown in Figure 9. An exponential decrease of pH can be seen. Initially, the pH of digesta was 4.27, due to the buffering effect of food. It decreased rapidly within the 1st hour of digestion, and reached < 2 after 75 min due to the continuous gastric secretion
and the gradual reduction of rice available for hydrolysis. The pH eventually reached 1.35, close to the pH of simulated gastric juice. This is in line with the findings of the in vivo study, in which pH was found to rise sharply to 4 to 7 upon ingestion of a meal, followed by gradual acidification due to gastric secretion (Dressman 1986).

Figure 9 shows the change in the solids content of emptied digesta. In the first 45 min, the solids content was maintained around 12%, and the profile shows a stable plateau. After that, the solids content had a linear decrease and reached 3% to 4% at the end of 3-h digestion. The plateau in the first 45 min may be due to the large amount of rice available for digestion relative to the amount of acid present in the HGS, so that the amount of acid became a limiting factor for the reaction (acid hydrolysis). As the trial proceeded, the amount of available rice decreased that caused a decrease in the solids amount released and subsequently lower solids content in emptied digesta. Figure 10 shows the change of solids fraction and digesta volume remaining in the HGS with digestion time. Corresponding to the decreasing rate of solids release, an exponential decrease in the solids fraction is shown. At the end of 3-h digestion, about 60% of the dry mass was emptied.

The overall size distribution of the solids after digestion in HGS is shown in Figure 11, taking into account both the emptied solids and the fraction remaining in the HGS. It shows that 70% to 80% of particulates were < 1.2 mm. A 10% to 15% of the solids present were in the size range 1.2 < d < 2.36 mm and 2.36 < d < 3.35 mm, respectively. Very few rice particulates were > 3.35 mm. As pylorus allows solids with size < 1 to 2 mm to empty into the duodenum, this result indicates that most rice kernels were fully disintegrated and available for emptying. Figure 11 also shows a significant difference in particle size distribution when the mechanical forces were changed, and the higher force (3.39 N) contraction produced a smaller average particle size, as indicated by a decreasing amount of large size particulates and an increase in the amount of small size particulates. This result proves that a stronger contraction force in the stomach should cause a greater level of food disintegration contributing to a smaller average particle size.

Conclusion
By incorporating peristaltic movement into the wall of a latex chamber, HGS successfully reproduces the peristaltic contraction of stomach wall and creates similar pattern of mechanical forces as in vivo that enables an improved simulation of digestion process and prediction of transformation of food constituents during gastric digestion. HGS is able to provide a reasonably realistic set of conditions that mimic the human digestion process. It could be used to study some of the changes in food constituents and gastric contents that occur during digestion, and the influence of physiological conditions, including acid and enzyme secretion and contraction forces on disintegration kinetics of foods and nutrient release. Although the force measurement and pH profiles showed good match with literature data, further comparison with in vivo data collected from human or animal trials would provide the ultimate validation of the predictive capability of the HGS. It should be also noted that the digestion process is extremely complicated. For example, neurohumoral regulation and ileal brake play a significant role in gastric digestion and emptying that are hard to simulate accurately. Also, it might be possible that other materials in addition to latex can be better in simulating stomach walls. Further improvements are being planned in order to make HGS more effective and precise in simulating gastric digestion.

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