Journal of Food Engineering 183 (2016) 1–8

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Gastric emptying and morphology of a 'near real' *in vitro* human stomach model (RD-IV-HSM)

Liding Chen [a], Yufen Xu [b], Tingting Fan [b], Zhenkai Liao [b], Peng Wu [b], Xuee Wu [b, **], Xiao Dong Chen [a, b, *]

[a] Food and Bioprocess Engineering Group, Suzhou Key Laboratory of Green Chemical Engineering, School of Chemical and Environmental Engineering, College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou City, Jiangsu 215123, PR China

[b] Department of Chemical Engineering and Biochemical Engineering, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen City, Fujian 361005, PR China

ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form
12 February 2016
Accepted 29 February 2016
Available online 2 March 2016

Keywords:
"Near-real" *in vitro* system
Rope-driven movement
Gastric morphology
Gastric emptying
Gastric sieving

ABSTRACT

Gastric morphology refers to the shape and the structural characteristics of the structure of the stomach. A 'near-real' *in vitro* human stomach model should not only mimic the physical movements to provide the digestion environment, but also provide realistic gastric morphology. In this work, quantitative evidences regarding the effects of gastric morphology including complex geometrical shape and inner wrinkles of a human stomach in a 'rope-driven' *in vitro* human stomach (RD-IV-HSM) have been investigated, which is relevant to the *in vivo* emptying behaviors. Contractive force in the antral area of the *in vitro* system was measured. The investigation has revealed that an initial lag phase and the buffering effect in digestion of solid food exist in the *in vitro* system. In addition, it has been found that the contractions created in the current device in antrum section contribute little to the gastric sieving phenomena thus the system needs further work to tackle this.

1. Introduction

The morphology of the mammalian stomach varies between species with regards to their dietary habits: the single forestomach of rodents can store a bulk of food to maintain a kind of steady state digestion (Gärtner, 2002), while the complex pluriloculate forestomachs of the ruminants provide spaces for cellulose fermentation (Hofmann, 1989). The primate, especially human, have a "J" shape single stomach, is divided into proximal and distal compartments. Gastric function is complicated by the natural structure of the compartment, with continuous food disintegration, digestion and selective emptying of finer materials in the distal compartment (Schulze, 2006). There is a growing interest in developing a realistic *in vitro* gastric model, and then use it to investigate the structural and chemical changes that occur when 'digesting' foods and medicines under controlled gastric conditions. These are primarily due to the fact that *in vivo* experiments are much harder to control and the results are less reproducible. *In vitro* systems can have advantages of better time-efficiency, labor-saving, providing rapidly screening food ingredients and better reproducibility. In addition, the *in vitro* experiments may usually require less ethical constraint (Hur et al., 2011; Kong and Singh, 2008a; Yoo and Chen, 2006). Most of the *in vitro* approaches mimic the human gastric digestion using rigid vessels such as stirred tanks and shake flasks, primarily due to their simplicity and convenience to use (Mahasukhonthachat et al., 2010). It is difficult to simulate the mechanics and hydromechanics in such rigid systems as those in an actual human stomach (Vardakou et al., 2011). Some of the more sophisticated semi-soft and soft gastric models were developed including the TNO gastric model (TIM-1) (Jedidi et al., 2014), the dynamic gastric model (DGM) (Chessa et al., 2014), the human gastric digestion simulator (GDS) (Kozu et al., 2014) and the human gastric simulator (HGS) (Guo et al., 2015). The contractive movements on their soft vessels were initiated by providing periodic water stress or using wheel rollers to simulate the dynamic contractions on a real stomach. However, they are not yet realistic, for

* Corresponding author. Food and Bioprocess Engineering Group, Suzhou Key Laboratory of Green Chemical Engineering, School of Chemical and Environmental Engineering, College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou City, Jiangsu 215123, PR China.
** Corresponding author.
E-mail addresses: xewu@xmu.edu.cn (X. Wu), xdchen@mail.suda.edu.cn (X.D. Chen).

http://dx.doi.org/10.1016/j.jfoodeng.2016.02.025
0260-8774/

example, the insoluble solid particles, especially when they are large, tend to settle in the tubular stomach of the TIM-1 system, which may account for at least one third of solid particles are retained in the stomach model after the gastric phase (Barker et al., 2014). For the 'inverted cone' systems such as the DGM systems, the periodic water stress has been found to be inadequate for solid food particles disintegrating and those digesta were too large in sizes for gastric sieving (Vardakou et al., 2011). Recently, mechanical rollers are used to enable peristaltic actions upon outer surface moving towards the bottom of the vessel (Which has the smallest diameter). A mesh net installed in the bottom of the soft vessel is used to simulate the gastric sieving in the HGS and GDS system (Kozu et al., 2014; Kong and Singh, 2010). Nevertheless, the distributions of the feed materials in the inverted cone systems are different from that in an actual human stomach due to the simplified gastric morphology (simple geometries and orientations), resulting in a reduction in the emptied lipid droplets (Mercuri et al., 2011) and a lack of the lag phase when emptying solid food (Kong and Singh, 2010).

In the current study, a new 'near-real' dynamic *in vitro* human stomach model named as the 'rope-driven' *in vitro* human stomach (RD-IV-HSM), has been designed to simulate the gastric morphology. The rope-driven mechanism is a way of producing contractive movement of the gastric wall. The mechanics of the RD-IV-HSM have been measured using the manometry and the breakdown of the pre-calibrated agar gel beads of various fracture strengths. The buckwheat samples were also masticated and used as a realistic sample and placed into the RD-IV-HSM system to observe the digestion and emptying behaviors, which are affected by the gastric morphology in the RD-IV-HSM.

2. Materials and methods

2.1. Materials

Buckwheat (See Sang Company, China) was purchased from a local grocery store in Suzhou City (Jiangsu Province, China). Buckwheat (100 g) was steamed with 150 g water for 40 min using a closed ceramic pot (GSD-12E, Tianji, China) until the starch was gelatinized. A food processor (CombiMax K600, Braun, Germany) was used as an artificial mouth. Cooked buckwheat (200 g) and artificial saliva (40 g) were mixed and grinded in the food processor using a stainless steel chopping blade (Braun 7051-140). The speed of the chopping blade was set at 1500 rpm to prepare the 'chewed' buckwheat particles before swallowing.

Artificial saliva was prepared by dissolving NaCl (0.88 g), KCl (0.48 g), $CaCl_2$ (0.44 g), NaHCO3 (5.2 g) and α-amylase(834 kU) in 1 L distilled water. Artificial gastric juice was prepared by dissolving NaCl (3.1 g), KCl (1.1 g), $CaCl_2$ (0.15 g), NaHCO3 (0.6 g), pepsin (1.0 g) and gastric mucin (1.5 g) in 1 L distilled water with pH of 1.6 adjusted using HCl. For making the *in vitro* human stomach model, liquid silicone, Human skin K-1001, was purchased from Kuwart Co. Ltd (China). α-Amylase, pepsin, mucin, rutin, DPPH and trolox were purchased from Sigma (Sigma–Aldrich, USA). Other chemicals were purchased from Sinopharm Chemical Reagent Co. Ltd. (China). Distilled water was purified using a Milli-Q system (Millipore Corp., France).

2.2. Development of RD-IV-HSM

The rope-driven *in vitro* human stomach (RD-IV-HSM) is composed of a soft human stomach model, a rope-driven system, a temperature controlled box, the secreting and emptying system (shown in Fig. 1).

The soft *in vitro* human stomach model was created by solidifying liquid silicone with the aid of an actual human stomach (specimen available at Xiamen University Medical School), as shown in Fig. 2, a "J" shape to simulate the gastric morphology. The thickness of the silicone skin is 6.0 ± 1.6 mm, in order to possess good elasticity and mechanical tolerance, which allows repeated squeezing without tear. The human stomach model has an approximate internal volume of 500 mL. In addition, this model has a wrinkled internal lumen, with the wrinkles on the inner-surface are approximately 5–10 mm wide each and 2–4 mm deep (See Fig. 2C). The wrinkled internal lumen is a significant improvement from those with smooth internal lumens (Chen et al., 2013a, 2013b). 20 silicone tubes (I.D. 1.5 mm, O.D. 2 mm) are connected to the gastric corpus in a random fashion to simulate the roles of gastric secretory glands. The other ends of the tubes are inlayed into a single connector (I.D. 10 mm, O.D. 16 mm), where a one-way valve invented in the same group (Chen et al., 2013b) is installed. The valve is used to prevent the contents in the stomach from returning to the secreting tubes. A peristaltic pump (YZ2515X, Baoding Longer, China) is used to drive artificial gastric juice into the secreting tubes. A diaphragm pump (FEM 08KT.18/RC, KNF, Germany) is used to drive gastric emptying and to collect the digesta through a PVC pipe (I.D. 6 mm, O.D. 8 mm).

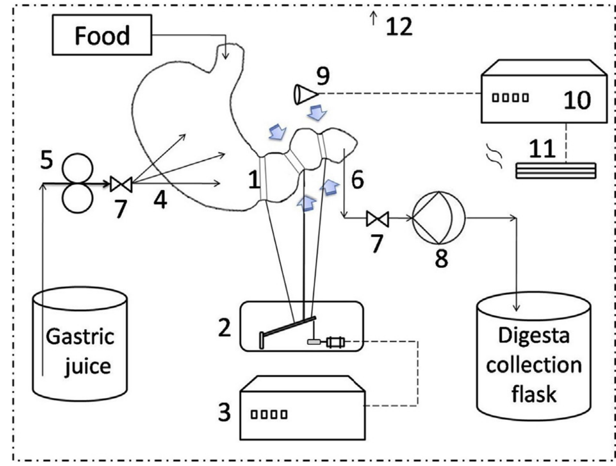

Fig. 1. Rope-driven *in vitro* human stomach: 1, *in vitro* human stomach; 2, rope-driven rig; 3, frequency controler; 4, gastric juice secreting tubes; 5, peristaltic pump; 6, gastric emptying tubes; 7, one-way valve; 8, diaphragm pump; 9, temperature sensor; 10, temperature controler; 11, electric heaters; 12, heat preservation box.

The RD-IV-HSM is intended to provide mechanical force on the gastric contents by a rope-driven system as shown in Fig. 3. In this system, the plexiglass shelves is used for not only supporting the human stomach model, but also supplying fixed positions for the fishing wires (8#). One end of the three ropes wrapped the antrum of the stomach model (10, 50, 90 mm away from the pylorus respectively), and the other ends are fasten on a pull rod through the holes on the shelf. When the step motor rotates the wire between the rod and motor shaft, the rod moves down and drives the ropes to fasten to produce contractions on the human stomach model. The stomach model can also be relaxed on the reversal operation. The step motor was set to create 3 contractions per minute on the stomach model, which is the actual contraction frequency on human stomach (Marciani et al., 2001b). The contraction can be reinforced by shortening the length of the rope or tied to be closer to the free end of the pull rod. The amplitude of the contractions on the model was set at 1 cm.

A temperature controlled plexiglass box was made and heated with electric heaters, which are controlled by a thermostat (WK-1, OHCHIDA, Germany). The temperature was maintained at 37 °C to