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Short communication

Mixing characterization of liquid contents in human gastric digestion simulator equipped with gastric secretion and emptying

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ABSTRACT

This study investigates mixing characteristics of the human stomach using a Gastric Digestion Simulator (GDS). The GDS simulates gastric peristalsis which is considered to have function of mixing gastric contents. The GDS has transparent observation windows for directly observing the contents during the experiment, enabling visualization of the mixing of the contents induced by simulated peristalsis. A continuous-type GDS (c-GDS) equipped with continuous gastric secretion and emptying was used in this study. A tracer experiment using stained model liquid foods (starch syrup solution) shows that model liquid food without starch syrup (Milli-Q) was mixed and emptied according to the theoretical equation of complete mixing flow, whereas model liquid foods with starch syrup concentration exceeding 15 wt% were emptied with almost no mixing according to the theoretical equation of plug flow. Mixing induced by simulated peristalsis would be weak and heterogeneous. There might also be a similar tendency in human stomach.

1. Introduction

The human stomach is an important part of the gastrointestinal tract (GI tract) in food digestion. Gastric digestion can be divided into chemical digestion and physical digestion. Chemical digestion is caused by gastric juice, whose main components are acid and enzymes, decomposing nutrients on a small scale. Physical digestion is caused by gastric peristalsis, which progresses as a wave by muscle contraction; this wave is called the Antral Contraction Wave (ACW). The ACW mainly occurs in the antrum (the distal part of the stomach), progressing toward the pylorus (the outlet of the stomach). This movement mixes ingested foods with gastric juice and breaks down solid food particles into smaller fractions [1]. In particular, intragastric mixing can be an important factor affecting the chemical enzyme reactions or residence of foods inside the stomach.

Gastric peristalsis movement has been observed from outside the human body using Magnetic Resonance Imaging (MRI) [2]. However, it is difficult to quantitatively understand physical phenomena inside the stomach. The intragastric flow-field induced by peristalsis has been numerically calculated using the Lattice Boltzmann method [3], Computational Fluid Dynamics [4,5], and the Particle Method [6]. In these computational simulations, retropulsive flow against the direction of peristalsis and eddy flow around peristalsis were observed. The maximum flow velocity was reported as several tens of mm/s. The tendency of intragastric flow was also observed using an *in vitro* gastric model [7,8]. This intragastric flow-field as calculated or measured by the hydrodynamic approach can induce intragastric mixing. Thus, the next step for understanding intragastric mixing is to experimentally investigate how strongly the flow-field induced by peristalsis mixes the gastric contents. When assuming that the stomach is a mixing reactor like Continuous Stirred-Tank Reactor or Plug Flow Reactor, the mixing characterization of the stomach as reactor is an interesting viewpoint from which to understand intragastric mixing.

A Human Gastric Digestion Simulator (GDS) has been developed in our research group to quantitatively analyze digestion phenomena and to directly observe the behavior of gastric contents [9]. Gastric peristalsis is simulated in GDS to analyze the effects of physical digestion: breaking down solid food particles and mixing contents. Several *in vitro* GI tract devices simulating gut-wall

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motion have been developed *e.g.* TIM [10], DGM [11], and HGS [12], whereas the unique character of GDS is the function of directly observing the inner contents though its transparent observation windows. The disintegration and/or swelling of food particles has been directly observed using GDS [9,13]. In addition, the GDS observation windows are especially suitable for visualizing the mixing of the contents. A batch-type GDS was previously used. All simulated gastric juice was injected into the GDS with food samples at the start of the GDS digestion experiment [9]. Furthermore, when GDS can simulate the continuous secretion of gastric juice and emptying of contents like an actual stomach, it will be possible to directly observe the mixing and to evaluate the mixing characteristics of the contents induced by simulated peristalsis.

The objective of this study is to analyze the characteristics of the human stomach as a mixing reactor using an improved GDS equipped with a continuous operation system. The functions of continuous secretion of simulated gastric juice and emptying of contents were added to GDS. A tracer experiment was conducted to quantitatively evaluate the mixing. Various concentrations of starch syrup solution were used as model liquid foods to investigate the effects of physical properties on intragastric mixing. The change in mixing characterization in GDS according to the variation of model liquid foods was analyzed by comparing each experiment result with the theoretical mixing characterization.

2. Materials and methods

2.1. Improvement of gastric digestion simulator for continuous operation

A continuous-type Gastric Digestion Simulator (c-GDS) is illustrated in Fig. 1a. c-GDS was improved based on our previous batch-type GDS [9]. c-GDS was developed to quantitatively analyze and directly observe gastric digestion by simulating gastric peristalsis, gastric secretion, and gastric emptying similarly to the human stomach. It consists of c-GDS vessels for digestion experiments, a temperature control system, a simulated gastric peristalsis system, and a secretion-emptying system.

A c-GDS vessel simulates the human antrum where peristalsis mainly occurs. The vessel volume of 550 mL is a reference to the human antrum volume [14]. Fig. 1b shows the geometry of the c-GDS vessel, simulated gastric peristalsis system, and secretion-emptying system. Gastric peristalsis is simulated by compressing deformable rubber walls using pairs of rollers; see our previous work for detailed mechanical system information [9]. The temperature inside the acrylic chamber is maintained by a heater, temperature sensor, and temperature controller. Liquid supplied by a diaphragm pump simulates gastric secretion. The liquid contents inside the c-GDS vessel are emptied by a programmable syringe pump that can simulate various emptying patterns. In general, solid components whose size is larger than 2 mm cannot be frequently emptied from the human stomach [1]. Considering this, a sieve with a pore size of 2 mm is inserted into the exit of the c-GDS vessel (Fig. 1b). Although the c-GDS vessel is rectangular and straight, unlike the actual tube-like J-shape (curved and twisted) of the antrum [3,5], our previous study using the Gastric Flow Simulator, with the same basic shape and peristalsis generation mechanism as c-GDS, demonstrated that major flow patterns and velocity orders were unchanged [8].

2.2. Preparation of model liquid foods and analysis of physical properties

Acid saccharification starch syrup with a moisture content of 25 wt% (B-75; Kato Kagaku Co., Ltd., Mihama, Japan) was dissolved

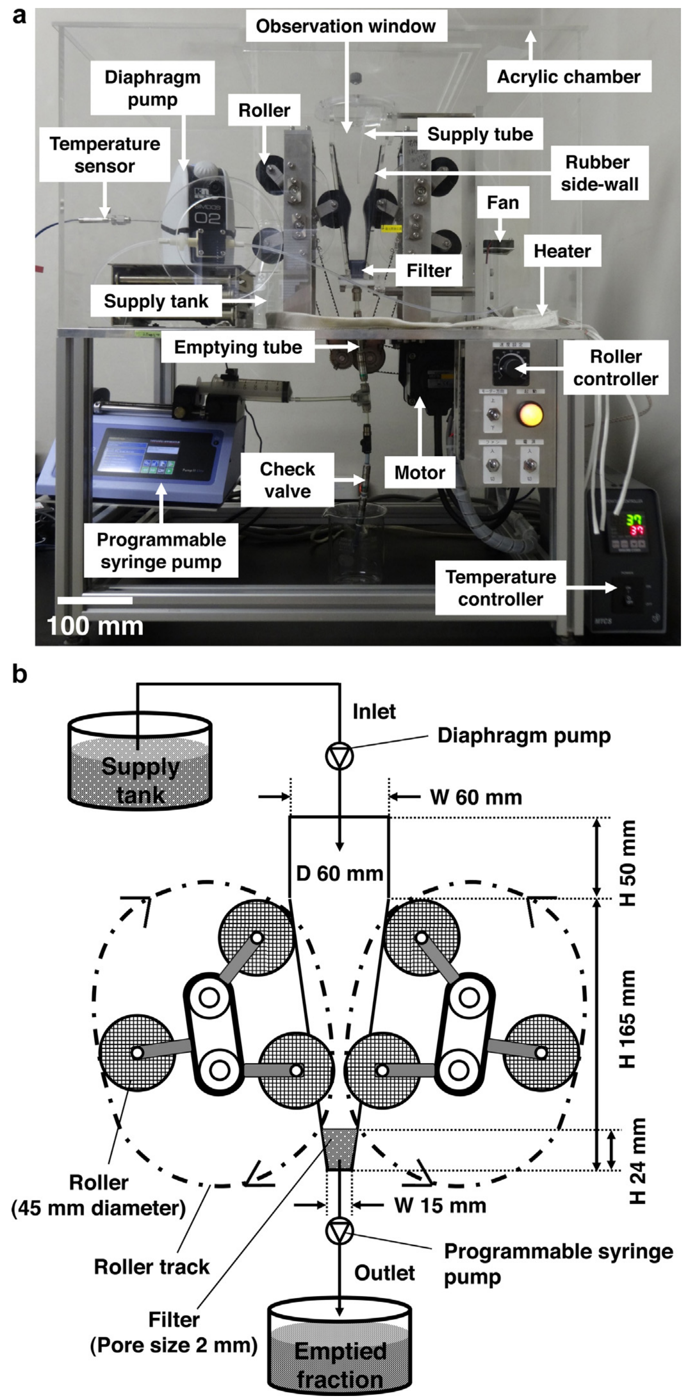

Fig. 1. Improved GDS for continuous operation (c-GDS). (a) Photograph. (b) Schematic diagram around c-GDS vessel. The schematic diagram in (b) was quoted in our previous study with partial modification [9].

in Milli-Q water as a model liquid food. To prepare model liquid foods with various physical properties, starch syrup concentrations of 0, 2, 15, 60, and 85 wt% were used. The model liquid foods are designated SS0, SS2, SS15, SS60, and SS85. The density of the model liquid foods was measured using a density meter (DA-130 N, Kyoto Electronics Manufacturing Co., Ltd., Kyoto, Japan), and the viscosity was measured using a Cannon-Fenske capillary viscometer (Cannon-Fenske (SO), Sibata Scientific Technology Co., Ltd., Saitama, Japan). The density and viscosity were measured at 37 °C, considering body temperature. The physical properties of each model liquid food are listed in Table 1.