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Understanding the fluid dynamics of gastric digestion using computational modeling

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Abstract

In this work a 3-D computational fluid dynamic (CFD) model of the stomach geometry and motility during digestion was developed, and to use it to analyze the flow behavior of gastric fluids with different rheological properties, and their effect on the motion of discrete food particles. The results were in good agreement with experimental data previously reported, and illustrated the significant effect of the fluid rheology on the flow field, pressure gradients, and particle motions within the stomach. From a boarder perspective, this work illustrates the unique capability of CFD to provide a fundamental understanding of the dynamics of gastric digestion.

Keywords: Gastric motility; Gastric flow; Particle trajectory; Rheology; Computational fluid dynamics.

1. Introduction

An underpinning knowledge of the fluid-dynamics of gastric contents is critical to understand and model the breakdown of food structures and consequent release of nutrients during digestion. Novel imaging technologies have recently enabled the in-vivo visualization of different gastric functions [1]; information that has been successfully used to develop a new generation of in vitro systems that offer unique opportunities to analyze the breakdown of food structures under different physiological conditions [2, 3]. However, due to the complex geometry and motility of the human stomach, the experimental characterization of the local, instantaneous, and 3-D behaviour of gastric flows has so far not been possible.

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The goal of this work was to develop a 3-D computational fluid dynamic (CFD) model of the gastric geometry and motility during digestion, and to use it to analyze the local flow behaviour and motion of discrete food particles, in association with fluids of different rheological properties.

2. Materials and methods

2.1. Geometrical model of the human stomach

There is no unique description of the size or shape of the human stomach. Its geometry varies significantly among individuals, and it is also continuously influenced by a large number of biological factors [4]. Based on this observation, a simplified 3-D model, capable of reproducing the average dimension of a human stomach in the postprandial period was developed [5]. As shown in Fig. 1, the model depicts the stomach as a "J"-shaped organ with a greater curvature of 34 cm, a maximum transverse diameter of 10 cm, a pylorus sphincter diameter of 1.2 cm, and a capacity of 0.9 L. Details regarding the construction and mesh scheme of the model are provided by Ferrua and Singh [5].

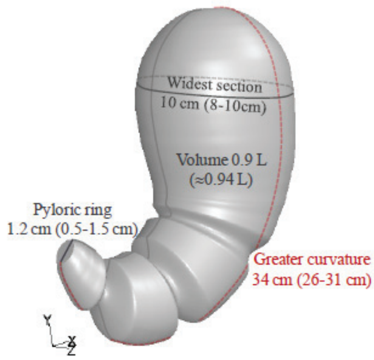

Fig. 1. Three-dimensional model of an average human stomach (dimensions reported in literature are informed in parenthesis)

2.2. Numerical model of gastric motility ("postprandial" period)

Immediately after eating, a "receptive relaxation" of the proximal wall allows the stomach to receive, and storage, the ingested meal without a significant increase in gastric pressure [6]. This response is then maintained by an "adaptive relaxation" that modulates gastric tone in response to the specific properties of the meal [7], and it is suspected to affect the distribution and emptying of gastric contents [8]. These responses (known as "gastric accommodation") have been analyzed in terms of overall changes in gastric volume [8, 9], but no accurate characterization of their dynamics have been published so far.

Another motor response during the postprandial period is the propagation of a series of regular peristaltic contractions waves (ACW) of increasing amplitude. These waves, which originate at the site of the gastric pacemaker and propagate towards the pylorus, are expected to develop the intragastric motions that promote the chemical and mechanical disintegration of food structures and their effect on the gastric emptying of liquids is still currently debated [1, 9]. Unlike "gastric accommodation", the dynamics of the ACWs have been successfully characterized by using advanced MRI techniques [9, 10].

Based on the dynamics of the ACWs provided by Pal et al. [10], the propagation of the ACW was numerically simulated by developing an algorithm that identified and relocated each node of the computational domain as a function of time. In particular, the ACWs were initiated every 20s at 15.1 cm from the pylorus, they were propagated with a constant horizontal linear speed of 0.23 cm.s-1, their width was assumed to be constant and equal to 2.0 cm along the stomach center-line, and their relative occlusion reached a value of 80% at 1.5 cm from the pylorus (Fig. 2). Since the stomach was modelled as a closed and incompressible flow system, to ensure continuity a series of tonic contractions were defined to compensate for the variation in the stomach's capacity caused by the ACWs [5]. These contractions were assumed to circumferentially deform the proximal wall of the stomach, with percentages of contraction/expansion that increased linearly from 0% (at the mid corpus) to a time dependent maximum value of up to 8% (at the top of the fundus).

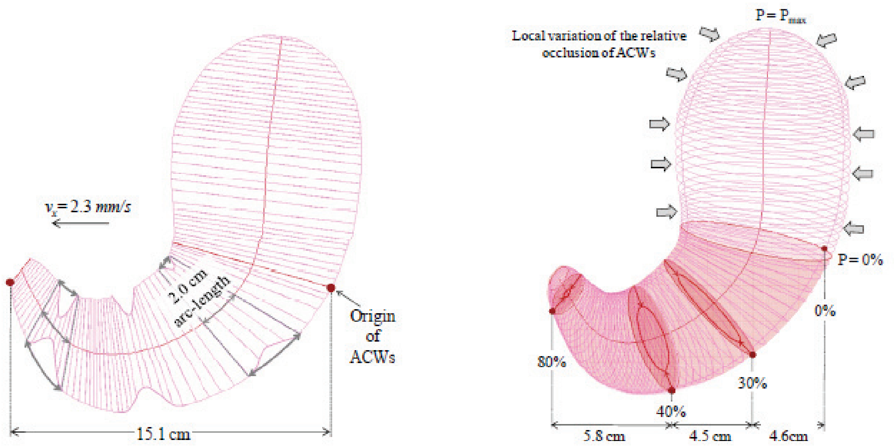

Fig. 2. Numerical characterization of the dynamics of the antral-contaction waves (ACWs)

2.3. Flow model

The fluid-dynamics of gastric flows were assumed incompressible and laminar, and were modeled by solving the continuity and momentum balances given by Equations 1 and 2, respectively.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial P}{\partial x_i} + \rho g_i \tag{2}$$

The energy boundary conditions at the surface of each strawberry were given by the continuity of temperature and heat flux (Equations 5 and 6, respectively).

For Newtonian fluids, the stress tensor (τ_{ij}) is directly proportional to the rate of strain, being the proportionality constant the viscosity of the fluid. In the case of some non-Newtonian fluids (such as shear-thinning fluids), the stress can be still related to the rate of strain by an apparent viscosity that depends on the shear rate of the fluid.

2.4. Physicochemical properties of gastric digestion

To investigate the possible effect of the rheological properties of the fluid on the dynamics of gastric flows, the flow behaviour of two Newtonian fluids (10-3 Pa.s and 1 Pa.s), and a non-Newtonian shear-thinning fluid (consistency index of 0.233 Pa.s0.59) were numerically investigated. Examples of liquid foods with these rheological properties are water, honey, and a 5.8 % T.S. tomato concentrate, respectively.

2.5. Motion of discrete food particles

The effect of the fluid viscosity on the motion of a series of discrete particles of food associated with the ingestion of a small cylinder of raw carrot (dia. 2 x 1 cm) was also investigated. The trajectory of the particles within the two Newtonian fluids under study was numerically tracked by integrating the force balance on the particle (Equation 3).

$$\frac{d\underline{u}_p}{dt} = F_D\left(\underline{u} - \underline{u}_p\right) + \frac{\underline{g}\left(\rho_p - \rho\right)}{\rho_p} \tag{3}$$

The amount and particle size distribution of the particles entering the stomach were determined based on their mass and size distribution in the bolus immediately before swallowing [11]. In particular, the sizes ranged between 0.4 mm and 4 mm, with a median value of 1.9 mm. The particles were "released" at the level of the esophago-gastric junction at a speed of 0.2 m/s [12].

2.6. Boundary conditions and numerical analysis

Although there is still a lack of scientifically-based information to correctly address the flow conditions at the gastric wall, based on a preliminary analysis aimed at numerically elucidate the effect of a free-slip condition on the fluid dynamics of the system, a non-slip condition was assumed and prescribed at the gastric wall. In addition, due to the small length scale of the roughness of the stomach lining and the presence of a mucous layer on top of it, the effect of the roughness of the wall was assumed negligible [12].

The model was solved using a commercial CFD solver Fluent^{TM} 6.3.26. Due to the periodicity of the gastric motility, the flow field became periodic after 48 s of simulated real time, repeating itself every 20s. Details regarding the numerical scheme and convergence criteria used are discussed by Ferrua and Singh [5].

3. Results & Discussion

3.1. Flow field behavior within the stomach model

Regardless of the rheological properties of the fluid, a highly 3-D flow was predicted within the model (Fig. 3). In addition, in good agreement with the classical description of gastric functions, the strongest fluid motions were always predicted within the antropyloric region, and a slow but constant recirculation of gastric fluid occurred between the top and bottom regions of the stomach [13].

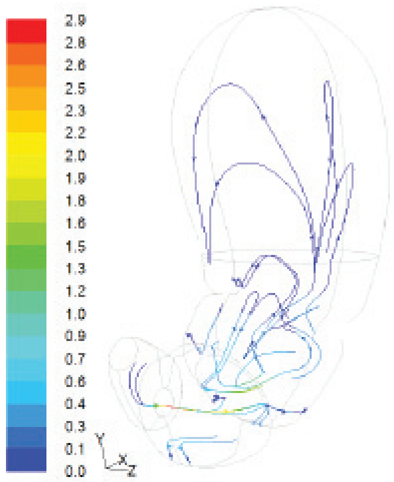

Fig. 3. Instantaneous streamlines of the flow field of a Newtonian (1x10^{-3} Pa.s) fluid at t + 10 s (maximum occlusion of gastric lumen 70%), colored by velocity magnitude (cm/s)

Unlike these overall features, the strength and local characteristics of the flow field within the antropyloric region were significantly affected by rheological properties of the fluid (as illustrated in Fig. 4).

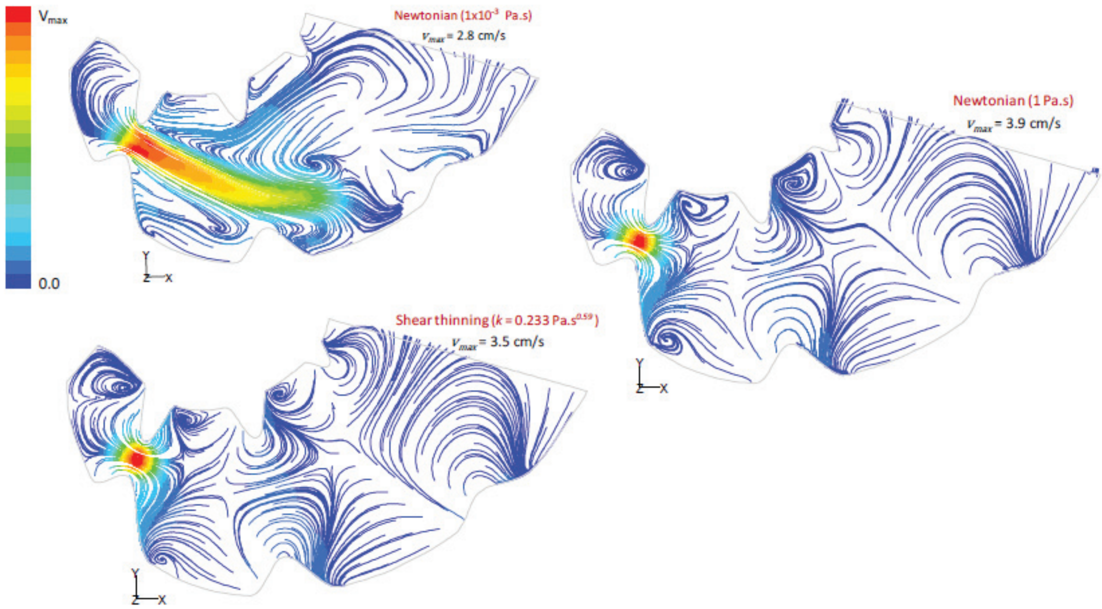

Fig. 4. Instantaneous streamlines within the stomach's middle plane at t + 10 s, colored by velocity (cm/s). a) Newtonian 1x10^{-3} Pa.s. b) Newtonian 1 Pa.s. C) Shear thinning fluid (k = 0.233 Pa.s$^{0.59}$)

In agreement with the classical description of gastric flow motions [4], the flow behaviour of a water-like fluid was characterized by strong retropulsive-like motions and eddy structures that extended throughout the entire antropyloric region (Fig. 4). As expected, the increasing speed and occlusion ratio of the ACW strengthened these flow features, leading to retropulsive velocities of up to 7.6 cm.s-1 and vorticity values of up to 10 s^{-1} in the most occluded region of the pyloric canal. However, by increasing the viscosity of the fluid, or changing its Newtonian characteristics, the formation of these flow structures was significantly diminished. Higher but much more localized retropulsive velocities developed at the core of the contracted section (reaching values of up to 12 $cm.s^{-1}$ and 8.0 $cm.s^{-1}$, respectively), and a lower and more confined vorticity field developed closer to the location of the ACW along the gastric wall. These differences can be explained by the improved action of viscous stresses, together with the presence of statinary conditions of the gastric wall, as discussed by Ferrua and Singh [5].

3.2. Pressure gradients within the stomach model

The overall behavior of the pressure fields were in good agreement with experimental data previously reported [14]. The higher pressures were always predicted at the leading edge of the most occluding ACW's peak, and the pressures distal to this wave increased successively faster as the wave approached the pylorus sphincter. However, unlike this overall behavior, the pressure gradients predicted were significantly affected by the rheological properties of the fluid [5]. In particular, pressure differences developed within the antropyloric region were directly proportional to the viscosity of the fluid (Fig. 5).

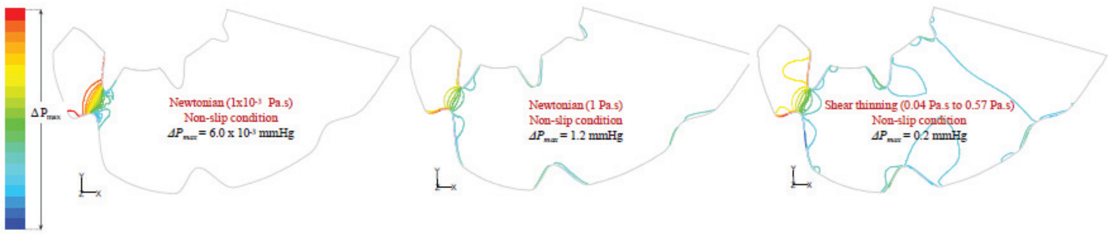

Fig. 5. Instantaneous pressure field within the stomach's middle plane at t + 10 s

3.3. Motion of discrete food particles

In the case of a water-like fluid (Newtonian, 10^{-3} Pa.s), the carrot particles settle over the greater curvature of the stomach within the first 30 seconds of being released into the stomach (Fig. 6). Although successive ACWs propel the particles forward, the higher occlusion of the ACW and the sigmoid shape of the terminal antrum force the particles back into the dependent portion of the stomach (even after experimenting a 95% loss of their initial mass, Fig. 7). These results are in very good agreement with experimental data obtained using real-time ultrasonography [15]. They show how (despite of the strong fluid motions developed within the stomach) buoyancy effects keep particles slightly denser than the fluid away from the rapid core stream, regardless of their size. They also point out the relevance of investigating how microstructural changes may affect, by modifying the physical properties of the particles, their dynamics during digestion (Fig. 7).

As illustrated in Fig. 6, in the case of a highly viscous Newtonian fluid (1 Pa.s), viscous effects stopped the particles immediately after being released into the slow gastric flow predicted at the location of the cardia Fig. 4b. In particular, this result also supports the theory that gastric dilution may actually play a critical role in determining the rheological properties of gastric contents associated with highly viscous meals [16].

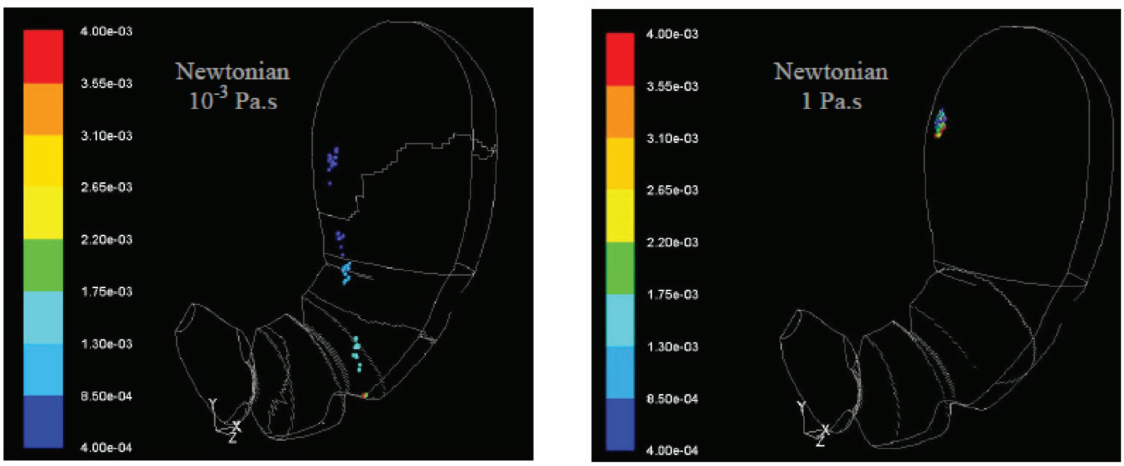

Fig. 6. Particles after 5 s of being injected into the stomach model (particles colored by diameter, m)

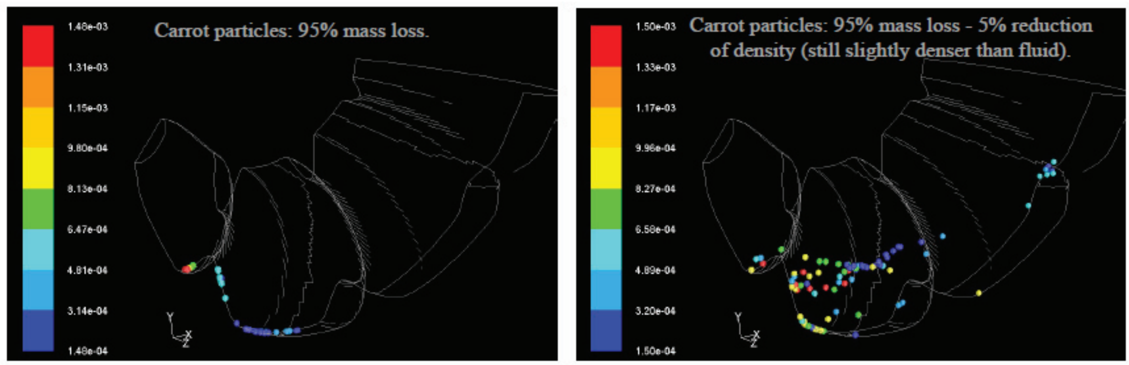

Fig. 7. Effect of mass loss and/or density changes on the dynamics of carrot particles within a low viscous Newtonian fluid flow (10^{-3} Pa.s)

4. Conclusions

The CFD model developed provided a unique insight into the dynamics of gastric contents, and illustrated the complex interaction of factors affecting the mechanisms driving digestion. This study showed the significant effect of the rheological properties of the fluid on the flow behaviour, pressure field and food-particle distribution within the stomach. It also suggests that, contrary to expectations, at the beginning of the digestion process the dynamics of discrete food particles may not be driven by the formation of strong fluid motions, but by a complex interaction of factors (such as the viscosity of the fluid, the size and relative density of the particles, and the geometrical configuration of the terminal antrum).

From a broader perspective, this work also illustrates the potential of CFD techniques to develop a fundamental understanding and modeling of the mechanisms involved in gastric digestion.

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