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# On the kinematics and efficiency of advective mixing during gastric digestion – A numerical analysis

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ABSTRACT

The mixing performance of gastric contents during digestion is expected to have a major role on the rate and final bioavailability of nutrients within the body. The aim of this study was to characterize the ability of the human stomach to advect gastric contents with different rheological properties. The flow behavior of two Newtonian fluids ($10^{-3}$ Pa s, 1 Pa s) and a pseudoplastic solution ($K$=0.223 Pa s$^{0.59}$) during gastric digestion were numerically characterized within a simplified 3D model of the stomach geometry and motility during the process (ANSYS-FLUENT). The advective performances of each of these gastric flows were determined by analyzing the spatial distribution and temporal history of their stretching abilities (Lagrangian analysis). Results illustrate the limited influence that large retropulsive and vortex structures have on the overall dynamics of gastric flows. Even within the distal region, more than 50% of the flow experienced velocity and shear values lower than 10% of their respective maximums. While chaotic, gastric advection was always relatively poor (with Lyapunov exponents an order of magnitude lower than those of a laminar stirred tank). Contrary to expectations, gastric rheology had only a minor role on the advective properties of the flow (particularly within the distal region). As viscosity increased above 1 St, the role of fluid viscosity became largely negligible. By characterizing the fluid dynamic and mixing conditions that develop during digestion, this work will inform the design of novel *in vitro* systems of enhanced biomechanical performance and facilitate a more accurate diagnosis of gastric digestion processes.



## 1. Introduction

The delivery of improved human health and well-being through food innovation relies on a better understanding of the conditions to which foods are exposed upon ingestion. Among them, the role of gastric digestion on the final delivery of optimal nutrition is being increasingly recognized (Wickham et al., 2012).

Second only to the mouth, the stomach is the main site for food disintegration. Changes in the compliance of the proximal wall allow the stomach to receive and store the ingested meal, while its disintegration is facilitated by a series of antral contraction waves (ACWs) that periodically compress, shear and mix gastric contents during the process (Schulze, 2006).

The use of advanced imaging technologies has recently demonstrated how the physical properties of the meal can modulate satiety and the rate of nutrient delivery to the small bowel, by simply modifying the intragastric distribution of the meal (Boulby et al., 1999; Faas et al., 2002; Kunz et al., 2005; Marciani et al., 2001, 2007, 2012). However, up to now little is known about the mechanisms underpinning the distribution and mixing of different digesta systems within the stomach.

Computational modeling has been recently used as an alternative approach to investigate the dynamics of gastric contents (Pal et al., 2004; Kozu et al., 2010; Ferrua and Singh, 2010; Ferrua et al., 2011; Imai et al., 2013). In general, these studies have focused on the behavior of different Newtonian fluids at the time of the most occluded ACW, and little has been done to characterize their mixing abilities. A pioneer work in this area, Pal et al. (2004) analyzed the dispersion of small particles within a 2D model of the human stomach and found that mixing was largely confined to its distal region. In close agreement, Imai et al. (2012) showed that the dispersion of tracer particles within a 3D model of the stomach was always enhanced by postures that completely fill this region. While informative, these two studies investigated only the advective properties of a single Newtonian fluid (1 Pa s) and based their analysis on the sole dispersion of discrete and inert particles within the domain. While associated to the bulk motions, the simple dispersion of particles within the domain cannot fully describe the advective properties of the flow (as for instance, particles trapped inside an eddy will experience little dispersion).

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In addition, the results obtained cannot provide a universal characterization of the advective performance of the flow, as the dispersion of the particles is highly dependent on the geometrical dimensions of the system.

From a fundamental perspective, the efficiency of advective mixing can be ultimately traced to the amount of stretching that differential material elements experience while being transported and deformed by the flow (Ottino, 1990). The faster and more chaotic their stretching growth within the domain, the faster and more efficient the mixing process. In this study, a numerical model (previously developed and validated) was used to characterize the kinematics and efficiency of advective mixing during gastric digestion by analyzing the stretching properties of gastric flows with different rheological properties.

## 2. Methods

### 2.1. Computational model of the human stomach

#### 2.1.1. Gastric geometry

A simplified 3D model that reproduces the shape and averaged dimensions of a human stomach was developed (Fig. 1a). The shape of the model was created using a series of 89 auxiliary circles that extended between the lesser and greater curvatures of a crossectional image of the human stomach (MedlinePlus). The model was then scaled to reproduce the average dimensions of a human stomach (Geliebter et al., 1992; Keet, 1993; Schulze, 2006).

A Cooper scheme was used to mesh the gastric domain (0.3 million elements of 0.15 cm size). Details regarding the geometrical construction of the model can be found in Ferrua and Singh (2010).

#### 2.1.2. Gastric motility

The periodic propagation of the ACWs was characterized based on *in vivo* data (Pal et al., 2004, 2007; Kwiatek et al., 2006; Treier et al., 2006). As illustrated in Fig. 1b, waves were initiated every 20 s ($T_w$) at 15 cm from the pylorus. They propagated down with constant horizontal speed and increasing amplitude, disappearing after 60s at 1.5 cm from the pylorus. The simulated contractions occluded the gastric lumen in the direction of the circles used to create the model. Based on the time period under study ($15T_w$), no gastric emptying was considered (Hausken et al., 1998). The compliance of the proximal wall was specified to compensate for the volumetric changes induced by the ACWs at each instant of time. The wall deformed radially, with levels of contraction/expansion linearly increasing from zero (at the mid-corpus) to a maximum (and time dependent) value at the top of the fundus (Fig. 1b).

#### 2.1.3. Boundary conditions

Boundary conditions were prescribed in terms of the velocity profile of the gastric wall and a no-slip condition for the fluids under study. Due to the symmetrical configuration of the model, a symmetry boundary was specified at its bisectional plane (i.e., only half of the stomach domain has been simulated).

### 2.2. Numerical analysis of gastric flows (Eulerian approach)

The flow behavior 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 $s^{0.59}$) was investigated over 15 ACWs periods. Examples of these fluids are water, honey and a 5.8% T.S. tomato juice, correspondingly (Steffe, 1996). The laminar and incompressible behavior of the flow was modeled by the mass and momentum balances:.

$$\nabla \cdot \underline{\mathbf{u}} = 0 \quad (1)$$

$$\rho\left(\frac{\partial \underline{\mathbf{u}}}{\partial t} + \underline{\mathbf{u}} \cdot \nabla \underline{\mathbf{u}}\right) = -\nabla P + \nabla \cdot \underline{\underline{\boldsymbol{\tau}}} + \rho \underline{\mathbf{g}} \quad (2)$$

where $\rho$ is the fluid density, $\underline{\mathbf{u}}$ is the velocity vector, $P$ is the pressure, $\underline{\underline{\boldsymbol{\tau}}}$ is the viscous stress tensor and $\underline{\mathbf{g}}$ is the acceleration due to gravity.

For Newtonian fluids, $\underline{\underline{\boldsymbol{\tau}}}$ relates to the rate of strain tensor ($\underline{\underline{\boldsymbol{\Gamma}}}$) through a constant fluid viscosity ($\mu$):

$$\underline{\underline{\boldsymbol{\tau}}} = 2\mu \underline{\underline{\boldsymbol{\Gamma}}} = \mu[\nabla \underline{\mathbf{u}} + (\nabla \underline{\mathbf{u}})^{T}] \quad (3)$$

For the shear thinning fluid, $\underline{\underline{\boldsymbol{\tau}}}$ also relates to $\underline{\underline{\boldsymbol{\Gamma}}}$ through an apparent viscosity ($\eta$) that itself depends on the magnitude of $\underline{\underline{\boldsymbol{\Gamma}}}$ (commonly known as shear rate, $\Gamma$).

$$\underline{\underline{\boldsymbol{\tau}}} = \eta(\Gamma)\, \underline{\underline{\boldsymbol{\Gamma}}} = K\,\Gamma^{n-1} \underline{\underline{\boldsymbol{\Gamma}}} \quad (4)$$

where $K$ is the consistency index (0.233 Pa $s^n$) and $n$ is the power-law index (0.59).

The dynamics of gastric flows was simulated every 0.05 s of real process time using ANSYS-Fluent 13$^{TM}$ (running on a computer with an 8 cores Intel CPU). Additional details with respect to the numerical algorithms used in the solution of gastric flows can be found in Ferrua and Singh (2010) and Ferrua et al. (2011).

The ability of the model to describe the pressure differences measured within the human stomach during digestion is discussed in Ferrua and Singh (2010). In addition, the ability of the model to predict the velocity field that develops inside a closed system by the peristaltic activity of its wall was also experimentally validated by Ferrua et al. (2011).

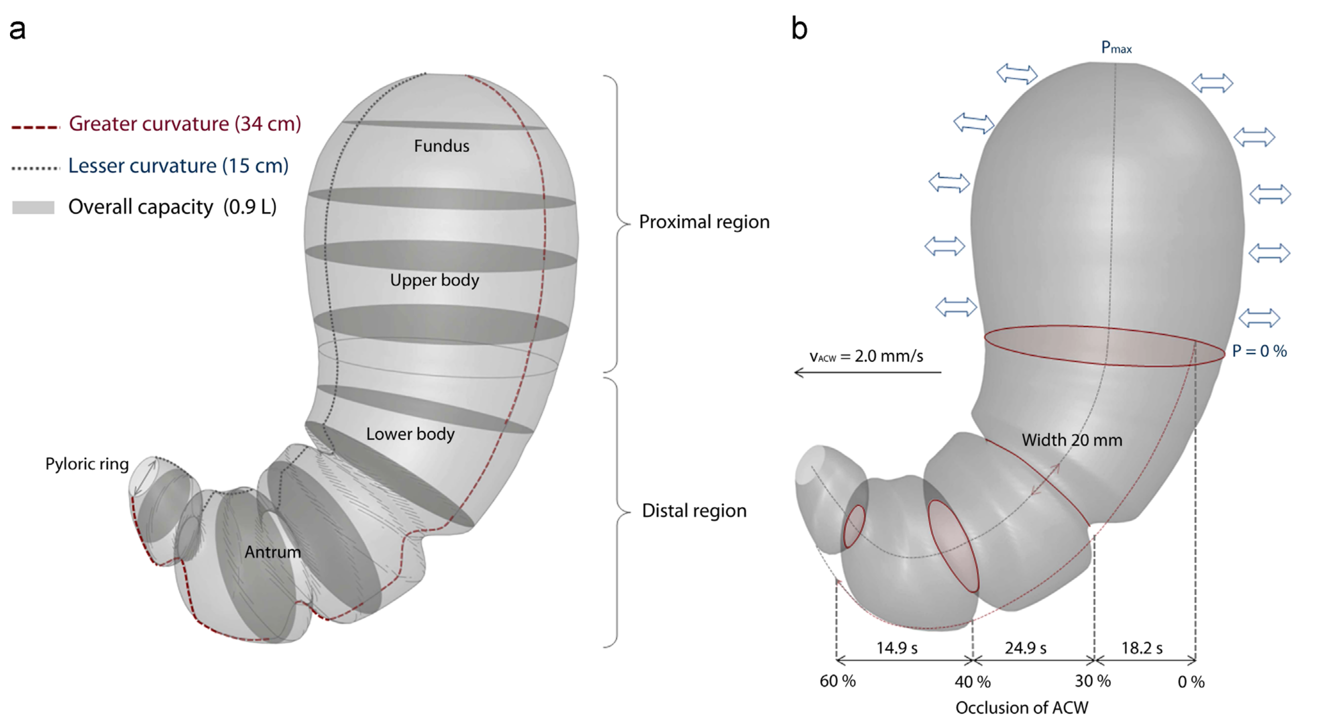


**Fig. 1.** a) Schematic diagram of the three dimensional model of the human stomach. b) Schematic description of the numerical characterization of gastric motility.