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REVIEW ARTICLE

Computational Models of the Fluid Mechanics of the Stomach

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Abstract | In the last 2 decades, the interest in developing computational fluid dynamics (CFD) models of the stomach has grown steadily. This bean-shaped organ plays a key role in our digestive system by chemically and physically processing food before emptying it into the intestines. The stomach walls drive the flow of the contents to achieve mixing, grinding, and emptying of the contents. Most computational models prescribe the motion of the walls and solve for the flow field inside the lumen, but some recent models also incorporate fluid–structure interaction between the muscles and the contents. Some models employ a simplified two-dimensional or axisymmetric geometry, while others use anatomically realistic stomach shapes. The emptying mechanism employed by the model and the inclusion, or lack thereof, of the pylorus further add to the nonconformity among the different models. In this review, we summarise these different CFD models of the stomach available in the literature. A comparison between these models with regard to their complexity, validation, and specificity is presented. While there has been rapid progress in the past few years, computational models are still far behind their other physiological counterparts, such as cardiovascular flows.

Keywords: *Computational fluid dynamics, Stomach biomechanics, Physiological flows*

pylorus Opening between the stomach and the duodenum (small intestines) whose closure is controlled by sphincter muscles

1 Introduction

It was just over 50 years ago that Peskin developed a computational model for flow inside the chamber of a heart[31]. Cardiovascular flow simulations have come a long way since then and we can now incorporate the structural mechanics as well as the electrophysiology of the muscles into computational models of cardiac hemodynamics[38]. The advancement in computational power and algorithms have increased the fidelity of computational models. In a review, Morris et al.[27] describe the wide variety of applications of computational fluid dynamics (CFD) in the field of cardiovascular medicine. Medical device developers use CFD for rapid and cost-effective prototyping, and researchers use it to measure and investigate quantities that are not measurable in experiments. Clinicians are now recognised as the third emerging user group of these models who can potentially utilise it for patient-specific diagnostics and surgery planning.

In contrast, the first computational model of the stomach emerged much later in 2004[28]. Even though the gastrointestinal system has been central to a plethora of modern diseases/disorders and surgeries, this lag of almost 3 decades with respect to cardiovascular models can be felt even in today's state of the art. Brandstaeter et al.[7] argue that despite the healthcare costs of stomach diseases being comparable to cardiovascular diseases, the current research efforts in the two domains are disproportionate. They further go on to conclude that, based on the dates

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of the first three-dimensional model and the first fluid–structure interaction model of each field, the modelling of stomach lags about 2 decades behind cardiovascular modelling.

To highlight the areas in which the gastric models are lagging and to identify the potential future directions, this review aims to outline the state-of-the-art CFD models of the stomach. We describe the role of fluid mechanics in gastric digestion, followed by a brief history of the transition from simple 2D models to anatomically realistic stomach models. Following that, we discuss the various applications of these models. The models from recent years incorporate additional complexities to simulate scenarios specific to a food type, disease, or surgery. This has opened up multiple potential future directions with utility for clinicians and food processing industries.

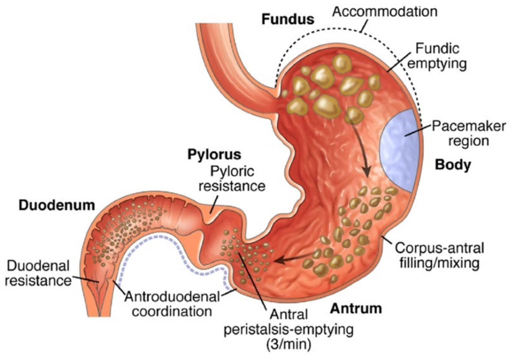

Figure 1: Schematic describing the three major parts of the stomach—fundus, body/corpus, and antrum—along with and duodenum[7]. The solid food particles are broken down by the high amplitude contractions inside the antrum. The fundus accommodates increasing volumes of incoming food while maintaining the pressure necessary to drive gastric emptying.

2 Fluid Mechanics of the Stomach

The stomach is a bean-shaped organ which, in the fed state, is filled with the ingested meal and wall secretions. It has three main regions—fundus, corpus, and antrum (Fig. 1). Although there are no separate compartments in the human stomach, these regions serve different functions as the wall motions and secretion glands vary from region to region. The fundus is a hemispherical dome at the top of the stomach that accommodates the incoming food and applies necessary pressure on the contents to drive emptying. The corpus is the middle part of the stomach that stores the contents. It also houses the pacemaker region of the stomach where the peristaltic contractions originate and propagate away from the fundus toward the antrum. As the contractions cross the corpus, they grow in amplitude and can occlude up to 40–50%[6,33] of the lumen by the time they reach the antrum. The high amplitude of contractions in the antrum is responsible for grinding and mixing the contents. The distal end of the stomach is connected to the duodenum, the proximal part of the small intestines, via the pyloric sphincter. The pylorus opens up to the incoming contraction waves to empty the contents into the intestines. Right before the contractions terminate at the pylorus, they collapse with an even larger amplitude (this collapse is termed as terminal antral contraction, TAC), almost completely occluding the lumen and propelling the trapped contents back into the stomach. This retropulsive jet plays an important role in the grinding and mixing of the food content. It is clear from this description that the wall motion is the strongest in the antrum. The fundus and most of the corpus are relatively quiescent, while the antrum has much more active flow dynamics.

The multiphase nature of the flow and the large variations in density and viscosity of the contents also add to the complexity of the flow problem. When a bolus of the chewed meal arrives in the stomach, the large solid components settle down under the action of gravity, and the compliant stomach walls sag as the arriving boluses stack in the sinus region of the antrum. The passing contractions entrain some of these solid particles into the flow and grind them into smaller sizes until they can pass through the pyloric orifice, which typically allows particles smaller than 2 mm to pass through. The viscosity and density of the contents can also vary over a large range. For example, the viscosity can be that of water, O(1) cP, or honey, O(10^3) cP; and the density can be that of oil (specific gravity ∼ 0.9), which would float on water, or solid foods, which would sink to the sinus. Alongside these physical processes, the chemical breakdown of the contents occurs simultaneously. The proximal stomach walls contains glands that secrete the acid and enzymes, which mix and react with the meal. Furthermore, many of the activities of the stomach described above are controlled by neurohormonal feedback loops in response to our physiology such as the caloric density of contents emptying into the intestines and blood sugar levels[16].

proximal A location that is closer to the mouth along the digestive tract (antonym: distal, farther away from the mouth).

retropulsive jet The jet in the wake of a peristalsis contraction.

It is evident that the fluid mechanics inside the stomach is complex and can cover a broad spectrum of flow types. The computational modelling of this flow additionally struggles with the disparity of associated time scales. The ingested meal can take up to several hours to empty from the stomach; however, ~ 3 contractions originate in the corpus every minute. The time-step size for spatially well-resolved simulations will be a fraction of a second, since it is determined by the flow through the 2 mm pylorus. Considering the computational expense, it becomes a challenge to simulate durations long enough to achieve significant digestion.

3 Mathematical Equations

The flow inside the stomach follows the incompressible Navier–Stokes equations:

$$\vec{\nabla} \cdot \vec{u} = 0, \tag{1}$$

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla}\right)\vec{u}\right) = -\vec{\nabla} p + \mu \nabla^2 \vec{u} + \rho \vec{g}. \tag{2}$$

In some cases, the stomach contents can exhibit non-Newtonian properties and the viscous diffusion term needs be modified accordingly, but here we assume the contents to be Newtonian in nature.

The stomach geometry can be an idealised geometry (generated as an axisymmetric shape made from 2D stomach sketches[10]) or it can be segmented from 3D MR imaging[18]—works involving both approaches are discussed in the review later. Generally, for both kinds of geometries, the walls kinematics are prescribed as a series of sinusoidal contractions moving longitudinally along the centerline. These contractions deform the stomach walls towards the centerline and propagate towards the pylorus. One way of mathematically prescribing the motility is as follows:

$$\vec{x}_w = \vec{x}_{w,0} + \lambda \vec{r}_w, \tag{3}$$

where $\vec{x}_w$ is the location of any point on the stomach wall, $\vec{x}_{w,0}$ is the initial location of the same point without any contractions, λ is the amount of deformation resulting from the contraction, and $\vec{r}_w$ is a vector from the point on the wall towards the closest point on the centerline. The deformation, λ, is constructed as a summation of equispaced travelling cosine waves multiplied by a function that varies their amplitude from one region to another. The expression looks like

$$\lambda(t,s) = \delta h(s) \sum_n \frac{F(s, s_{0,n})}{2}\left(\cos\left(2\pi \frac{s - s_{0,n}}{W_p}\right) + 1\right), \tag{4}$$

where s is the distance along the centerline, $s_{0,n}$ is the location of the centre of the n^{th} contraction wave, W_p is the width of the contraction, the function $F(s, s_{0,n})$ is a top hat function that is unity only over the distance W_p centred around $s_{0,n}$ and zero everywhere else, δ is a constant that defines the overall strength of these contractions, and $h(s)$ is the function that varies the amplitude of these contractions along the centerline. Some examples of formulating these functions and parameters can be found in another work[18]. The wave amplitude δ remains the parameter of popular interest in many works as it is varied to influence the overall strength of contractions and mimic some motility disorder scenarios such as antral hypomotility. Lower amplitude leads to weaker retrograde jets and poorer mixing of contents.

A few recent studies also solve a fluid–structure interaction problem to define the motion of the stomach walls, in which case the stresses in the wall muscle fibres are calculated and applied on to the adjacent fluid

$$\vec{f}^e(\vec{x},t) = \int_{\forall} \vec{F}^e(\vec{q},t) H\left(\vec{x} - \chi(\vec{q},t)\right) d\vec{q}, \tag{5}$$

where $\vec{f}^e$ is the Eulerian force density that needs to be added to the fluid momentum equation, $H(x)$ is the Dirac delta function, and $\vec{F}^e$ is the Lagrangian description of the force density based on the current position of the wall ($\vec{\chi}$) and is computed using the first Piola–Kirchoff stress tensor (see[2] for example).

Many studies include an additional component dissolved inside the liquid contents of the stomach. The dissolved component—which can be an enzyme, acid (H^+ ions) or dissolved nutrients—is commonly modelled as a passive scalar transported by the flow. The advection–diffusion equation is solved to track the transportation of scalar(s)

$$\frac{\partial c}{\partial t} + \vec{u} \cdot \vec{\nabla} c = D \nabla^2 c + S, \tag{6}$$

where c is the concentration of the scalar, D is the coefficient of diffusion, and S is the volume source term that can account for the production as a result of chemical reaction (e.g., protein hydrolysis). These dissolved components tend to have a low coefficient of diffusion and the transportation is advection dominated driven primarily by the active flow inside the antrum[37].

To give a better idea of the time and velocity scales of the problem, it is worth mentioning that the stomach wall motion is quite slow: contractions move at speeds of $2 - 3$ mm sec^{-1} and originate every 20 sec. The Reynolds number, $Re = UL/\nu$, based on the contraction velocity, contraction width, and the kinematic viscosity of water, is between 10 and 100[18], denoting that the flow is laminar. More viscous meals would have an even lower Reynolds number.

4 From 2D to Anatomically Realistic Stomach models

Like most applications of CFD, the initial models of the stomach were two-dimensional. Pal et al.[28] were the first to develop a computational model of the stomach in 2004 that solved the flow field inside the stomach outline using a lattice-Boltzmann method. The contractions observed in the MRI were parameterised and then incorporated into the model as deformations on lesser and greater curvatures. Despite being an initial attempt at developing an organ-level model of the stomach, their seminal work remains relevant even today as many current studies use the motility parameters reported in their work[30]. They managed to capture the characteristic features of the flow, incorporated the synchronised opening/closing of the pylorus, and also identified the relatively high rate of mixing in the antrum compared to the proximal stomach. In a follow-up work in 2007[29], their simulations reported rapid emptying of contents that lay on a narrow path along the lesser curvature funnelling contents from the proximal stomach. The fluid parcels on this path emptied long before those that did not, even if the latter were closer to the pylorus.

Three-dimensional models started to emerge soon after the above studies; however, two-dimensional models have continued to be a part of the discourse. Kozu et al.[17] created a two-dimensional model of just the antrum, represented as a channel. One half of the channel tapered into a closed end (representing a closed pylorus), while the other half had a uniform height. They studied the effect of viscosity on the retropulsive flow caused by the contractions. They also studied the mixing induced by the contractions by looking at the mass transfer of an enzyme (pepsin) secreted from the gastric walls. It must be pointed out that this idea is only good for quantifying mixing, and should not be extended to the subsequent chemical breakdown of proteins by pepsin, because that requires a full organ model of the stomach as pepsin is secreted only by the proximal walls of the stomach[5,6]. Alokaily et al.[4] conducted a parametric study of contraction wave parameters using a tapered channel with moving sinusoidal contractions as a model of the antrum (see Fig. 2). They varied the contraction velocity, width, and amplitude (or the occlusion) along with the fluid viscosity, to look at their effects on the retropulsive flow and the mixing efficiency.

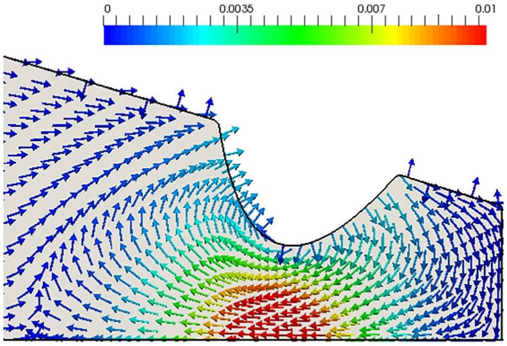

Figure 2: The 2D model of the antrum by Alokaily et al.[4]. The indentation moves from left to right towards a closed pylorus and the colors indicate the velocity of the contents in m/s.

The low cost of 2D models made them a good tool to qualitatively capture the flow inside the antrum. Researchers could study the sensitivity of this flow towards the contraction parameters and the viscosity of the contents. However, these models are limited in their application as it is difficult to generate physiologically relevant data. To compare to an equivalent in-vivo measurement, for example, accounting for the three-dimensionality of the stomach becomes important.

The first 3D model used a simplified geometry of the stomach that was symmetric about the central plane[11,35]. It was constructed by connecting a series of circles drawn out of the plane of a typical outline of the stomach. With a closed pylorus, the flow field was solved using the software package Fluent (ANSYS, Inc., Canonsburg, PA, USA) and was reported to be highly three-dimensional. The retropulsive jet, as well as recirculation eddies in the wake of the contractions, were sensitive to food viscosity. Around the same time, Imai et al.[13] used an anatomically realistic model of the stomach to study the mixing inside the stomach in different postures. They incorporated free surface modelling, but the model did not feature the opening/closing mechanism of the pylorus.

Since then, both idealised three-dimensional[2,21] as well as anatomically realistic models[14,20] have been published. We will now discuss the recent models in the context of their applications. Before proceeding, two noteworthy observations worth highlighting regarding the trend of stomach CFD models are, first, all anatomically realistic models use the virtual human population database[12], and second, most models do not incorporate the opening/closing of the pylorus—leaving it either permanently open or closed[30]. Even those that include the pylorus, a tonic contraction or a fundic pressure implementation is missing which is the primary driving mechanism of gastric emptying.

5 Gastric Disorders

Improved fidelity of anatomically realistic models has enabled the biofluid dynamics study of gastric disorders, particularly motility disorders. Most studies that focus on the effect of contraction wave parameters are partly motivated by similar changes being observed in gastric motility disorders such as gastroparesis.

In 2016, Miyagawa et al.[26] used the lattice-Boltzmann method to solve the flow field in a stomach with a closed pylorus. They reported the mixing efficiency of the stomach against changes in the meal viscosity and the contraction parameters. Gastric motility was characterised by a Reynolds and a Strouhal number based on meal viscosity and contraction wave properties. Ishida et al.[14] added a pylorus to the model and studied the effect of impaired coordination between contractions and the opening/closing of pylorus for different meal viscosities. The emptying rate of the control case was found close to the experimental values, and the impairment was found to directly affect the trans-pyloric flow, leading to altered emptying rates and bile reflux. More recently, Ebara et. al.[9] extended that model to study the effect of amplitude and frequency on gastric emptying rates.

Using a biomechanical Smoothed-Particle-Hydrodynamics (B-SPH) model, Harrison et al.[25] studied the effect of the frequency of contractions on the mixing and emptying of contents with a specified pressure head and a permanently open pylorus. Emptying was driven by the peristaltic contractions as well as the pressure head, and more frequent contractions were found to have higher emptying rates. However, the relaxation at the end of a contraction led to reverse flow, because the model featured a permanently open pylorus.

Another stomach model, based on the immersed boundary method (IBM), was demonstrated by Seo et al.[34] and Lee et al.[20] without and with pylorus, respectively, in 2022. They studied the dissolution of an orally ingested pill whose six-degrees-of-freedom motion was governed by the equations of linear and angular momentum under the action of hydrodynamic and gravitational forces, and the dissolved active pharmaceutical agent was considered as a passive scalar (Fig. 3). The rate of dissolution was found to be sensitive to the effects of dysmotility, reduced amplitude, and/or frequency of the contractions due to gastroparesis. Posture, i.e., the direction of gravity, influenced the settling location of the pill and thereby affected the rate of dissolution.

6 Modelling Chemo-Fluid Dynamics of the Stomach

The fluid dynamics inside the stomach is tightly coupled with the chemistry of the gastric phase of digestion. The secreted acid and enzymes are transported throughout the lumen to act on the ingested food. Since the enzymes are secreted from the proximal walls, while the mixing is mostly carried out in the antrum, simulating these processes requires a full organ model. Such models have shown up in the literature only recently.

Trusov et al.[37] used a simplified model of the antro-duodenal region with an open pylorus to implement the coupling of chemistry with the flow. Although they used an idealised stomach geometry that considered only the antro-duodenal region, it is still worth mentioning here as this model incorporated acid secretion as well as hydrolysis of food nutrients into the model by treating them as passive scalars. The model was used to study the effect of functional acid and alkaline secretion disorders on the digestion of food components.

In 2021, using an idealised stomach geometry that also featured a permanently open pylorus, Li and Jin[21] studied the effect of TAC on the mixing of contents and the distribution of pH inside the lumen (Fig. 4). The model used the open-source software package OpenFOAM, and the gastric juice secreted from the walls contained H^+ ions that were treated as passive scalars. Later, they modified this model to simulate the digestion of meat proteins[22] by treating smaller solid food particles as passive scalars and by including a food matrix in the distal stomach that provides resistance to the passing flow, representing the accumulation of settled larger particles. Withstanding this matrix, the particles emptied via a pathway close to the inner surface.

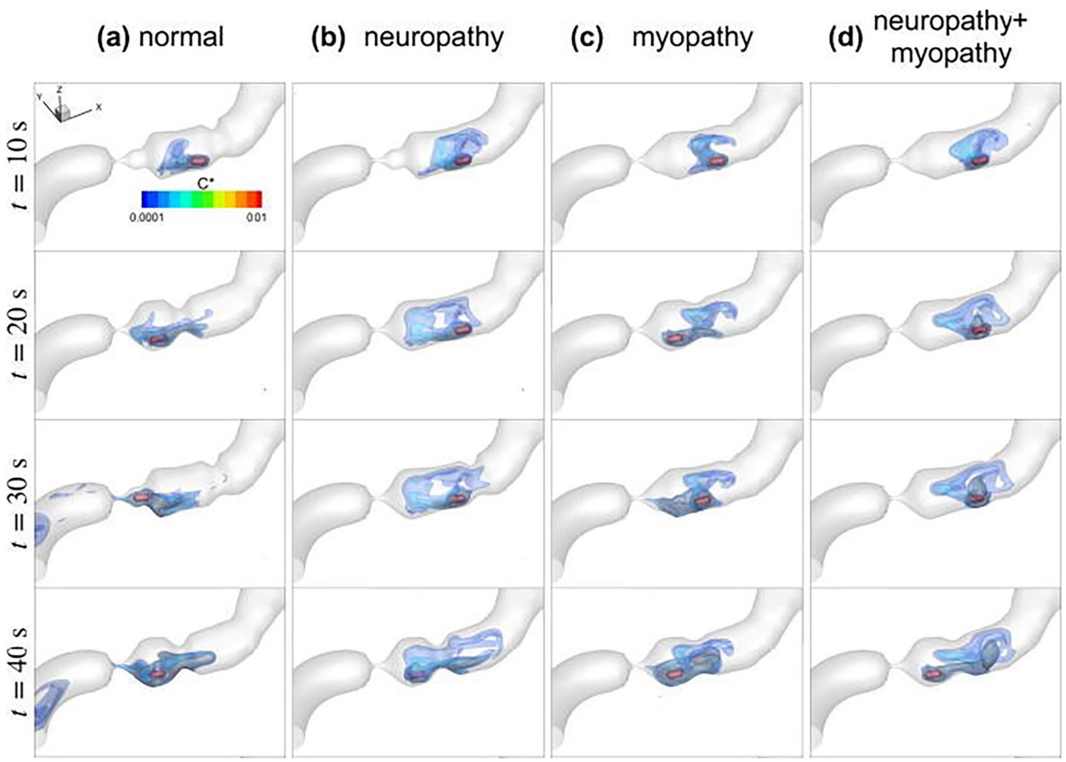

Figure 3: Comparing the dissolution of an orally ingested pill in different kinds of stomach motility disorders[20].

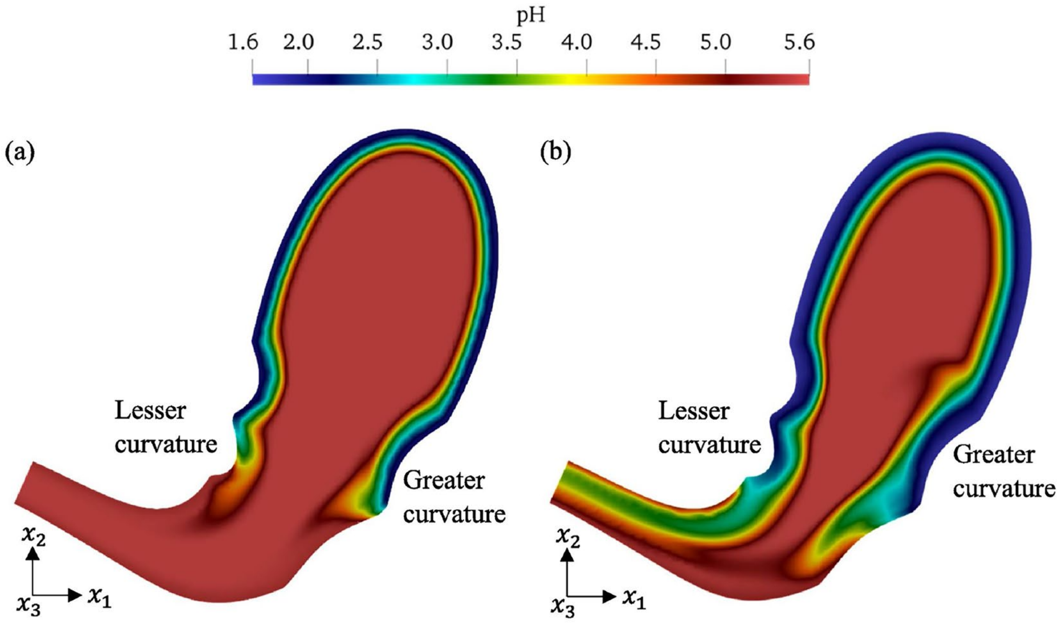

Figure 4: The distribution of pH modelled by Li and Jin[21] at **a** $t = 200$ sec and **b** $t = 600$ sec. The H^+ ions are secreted from the proximal stomach walls.

Kuhar et. al.[18] incorporated the chemistry of protein hydrolysis into the IBM-based model mentioned earlier. A proteolytic enzyme (pepsin) was secreted from the proximal walls that hydrolysed the protein inside the liquid meal as per a first-order catalytic reaction (Fig. 5). While the

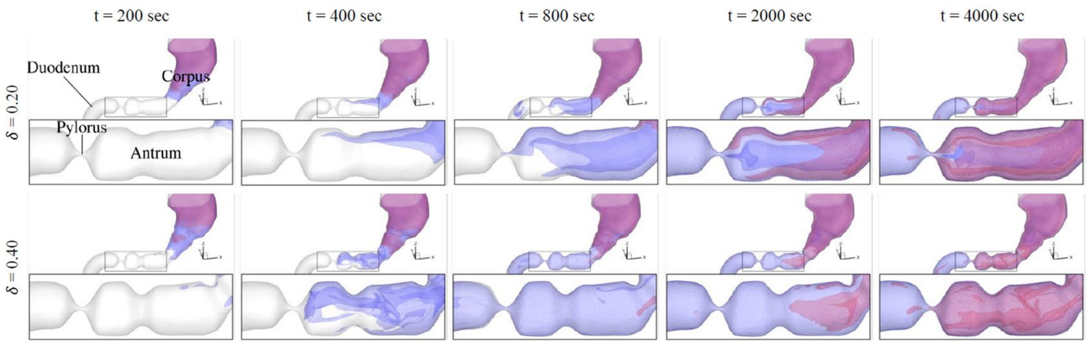

Figure 5: Protein hydrolysis for a weaker motility case (row 1) and a healthy case (row 2) over an hour long digestion period as modelled by Kuhar et al.[18]. The concentration iso-surfaces of the enzyme (pepsin) are shown in pink and those for the hydrolysed protein are shown in blue.

other studies have studied up to a few dozen contractions, this study simulated a duration of over 1 h to capture the digestion phenomenon over realistic time scales by making use of the periodicity of the flow. The emptying rate was validated against in-vivo data and the effect of reduced contraction amplitudes on the mixing and the subsequent rate of protein hydrolysis and gastric emptying was quantified. The findings suggested that the consequences of motility disorders go beyond just altered emptying rates, and they also affect the rate of digestion of contents due to poorer mixing. The reaction interfaces were more widespread with a larger surface area for cases with a stronger motility.

7 Effect of Surgery

Nearly a quarter million bariatric surgery procedures, such as sleeve gastrectomy, Roux-en-Y gastric bypass, adjustable gastric band, and gastric balloons, are carried out each year in the US[1]. However, insights from biomechanics/biophysics play little or no role in these procedures nor do these procedures exploit the latest tools in modelling and simulation to optimise the outcome for the patients. Due to the variabilities in patient outcome, currently, less than 1% of morbidly obese patients undergo bariatric surgery[3,8]. This is yet another arena where the application of biomechanical modelling to gastric digestion lags other fields of biomedicine (cardiovascular, respiration, inhaled drug delivery, musculoskeletal, etc.).

Computational modelling of surgery is one of the most recent applications in this field. In 2023, Zhang et al.[39] used ANSYS Fluent to develop a rigid wall model, with a steady flow, of two stomach shapes corresponding to conventional and the stomach partitioning gastrojejunostomy surgeries (Fig. 6). For patients suffering from gastric outlet obstruction, these surgeries create a new connection between the stomach and the intestines. The model identified that the stomach partitioning surgery offered a better emptying rate performance of the two approaches by discharging contents at a higher speed and ensuring that lesser amounts of contents flowed to the pylorus. Although the model used a rigid stomach, it demonstrates the potential of computational models in contributing to clinical hypotheses.

A 2024 study by Kuhar et al.[19] explores the consequences of pyloric intervention procedures on patients with different phenotypes of gastroparesis (Fig. 7). These surgeries disrupt the sphincter function of the pylorus keeping it open with the goal of ameliorating symptoms arising out of a reduced gastric emptying rate (i.e., gastroparesis). The study improved upon the earlier IBM-based model by incorporating the effect of gastric tone which drives gastric emptying. It is also the only study that compares trans-pyloric pressure gradients against *in-vivo* data. A decreased gastric tone was found to more severely impact the gastric emptying rate as compared to decreased motility. Furthermore, pyloric surgery improved the emptying rate performance only if the gastroparesis case maintained some of its gastric tone. The study also observed bile reflux from the duodenum back into the stomach due to the disrupted sphincter and presented a possible reason for a significant portion of the patients not responding to these surgeries.

There is a need for more computational studies to explore the effects of surgery. However, this research direction runs into multiple issues

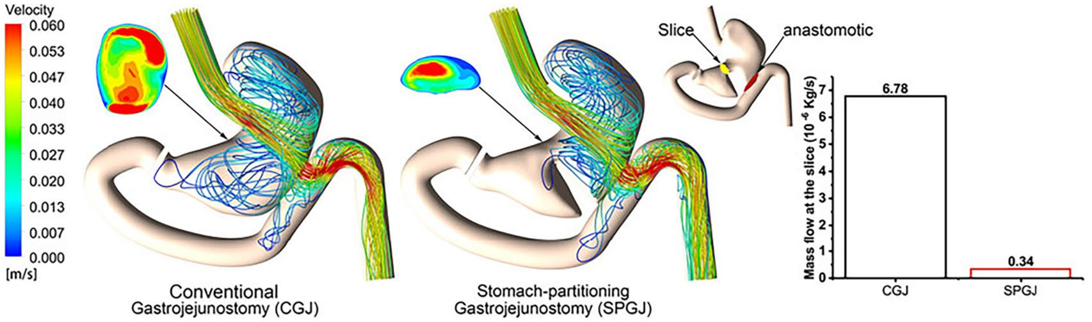

Figure 6: A comparison of flow fields in two types of gastrojejunostomy by Zhang et al.[39].

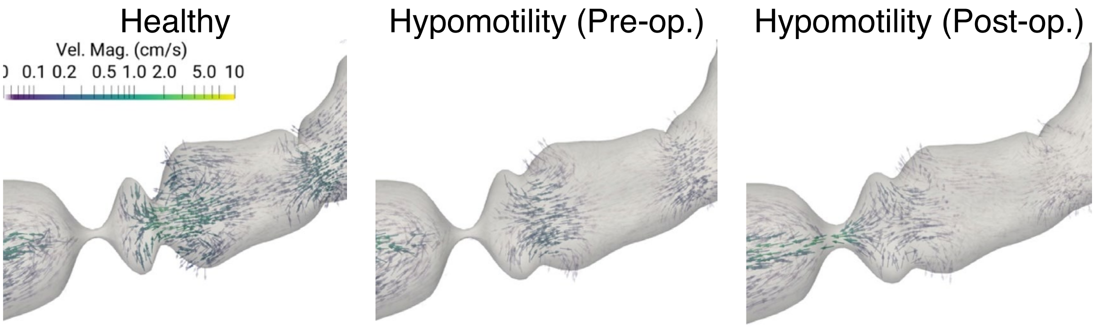

Figure 7: Velocity vector field of the antro-duodenal region at an instance during TAC of a healthy stomach and a stomach with antral hypomotility (arising from motility disorder) before and after pyloric enlargement procedure that disrupts the sphincter function to improve the emptying rate of the stomach.

that require a deeper in-vivo–in-silico collaboration. A quantitative description of the changes in the stomach geometries after surgery is lacking. Accurate measurements of stomach motility are hard to obtain even on healthy stomachs. The disruption of muscle fibres due to surgical cuts and the resulting variation in the peristaltic contraction waves remains unknown and would require the simultaneous modelling of the electrophysiology of the stomach walls.

8 Multiphase Fluid Dynamics

The discussion so far mostly discussed the cases with the stomach containing a purely liquid meal. However, the ingested meal may be liquid or a multiphase mixture of liquids and solids with different densities and viscosities. Gastric juice secreted by the stomach, which along with salivary secretions and ingested liquids, may occupy a significant (> 1 Litre) volume in a fed stomach, and also has fluid properties that might be different from the rest of the contents. Density differences result in gravitational settling (i.e., sedimentation) and layering of the gastric contents. For instance, low-density lipids typically form the top layer, whereas denser carbohydrates, protein-rich foods and solid food particles usually form the bottom layer[32]. This layering has significant implications for the mixing and digestion of these different food components. Alongside, the processing of solid food particles in the stomach involves particle–particle, particle–wall, and particle–fluid interactions. These processes determine the rate of dissolution of solid food particles, and accurate modelling of solid–particle dissolution is yet another multiphase flow problem inside the stomach.

Studying the effect of buoyancy when the stomach contains fluids of different densities has been modelled by a few studies. With an idealised 3D stomach geometry and a permanently open pylorus, Li et al.[23] included multiple food boluses by treating them as separate fluids. The heavier boluses settled and intermixed over 10 min to form chyme (Fig. 8). As already mentioned earlier, they later accounted for the settled large particles as a food matrix that resists the passing flow[22]. Acharya et al.[2] simulated gravity-driven bolus settling in the stomach using the immersed

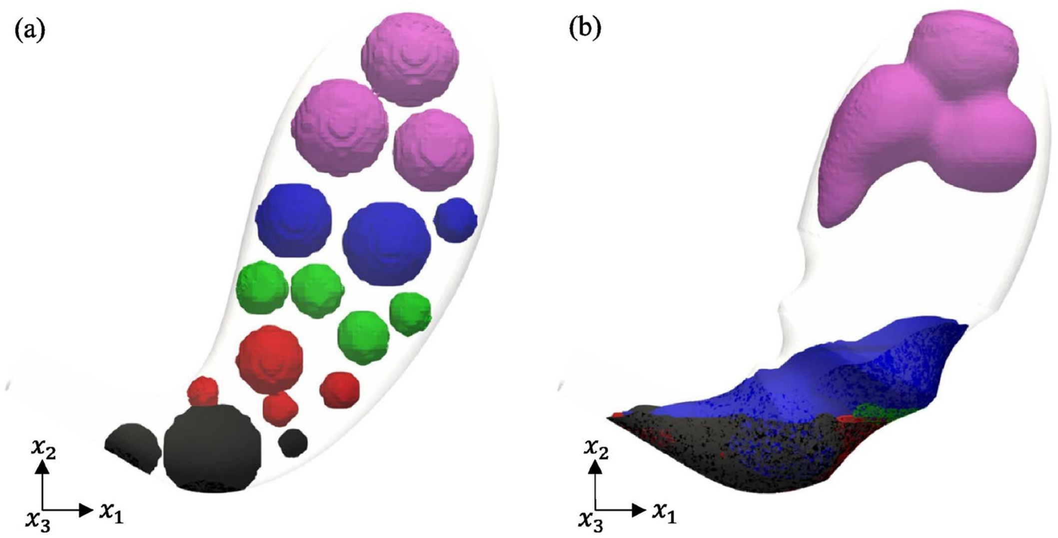

Figure 8: Food bolus of different densities move under the action of gravity to form layers. The settled contents mix with each other to form chyme[23].

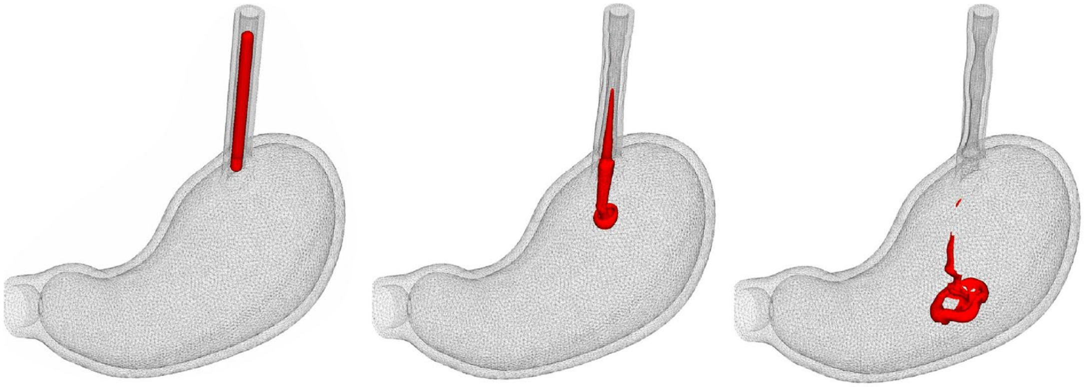

Figure 9: The evolution of the surface of a gravity-driven bolus emptying from the esophagus into the stomach as simulated by the immersed boundary finite-element (IBFE) method by Acharya et al.[2].

boundary finite-element (IBFE) method and incorporated the fluid–structure interaction of muscle fibres with the contents (Fig. 9). They also simulated reverse flow scenarios, such as belching or acid reflux, using a bolus of lower density. Recently, Liu et al.[24] simulated the turnover of an aqueous layer lying on top of a lower density fatty layer in a non-deforming stomach. They observed that buoyancy-driven flow effects happened much faster than the time scale of wall contractions.

The modelling of solid food particles and their breakdown by the wall contractions, a phenomenon known as trituration, has not been attempted yet. The food bolus entering the stomach can contain particles ranging from below 0.4 mm to larger than 4 mm[15]. The sieving function of the pylorus allows only particles smaller than $\sim 1-2$ mm to empty into the duodenum. The grinding of the large particles under the shearing action of the wall motion is a challenging multiphase flow problem. While the multi-fluid approach remains a popular choice among the few studies that include solid food particles, a range of particle sizes is particularly difficult to incorporate in multi-fluid approaches[36]; hence, a Lagrangian point-particle method (for small particles) or a particle-resolved approach (for large particles) would be more suitable to study the details of the shear forces acting on these particles. In an ongoing work with the immersed boundary-based model mentioned earlier, we are modelling the erosion of a set of large food particles using the

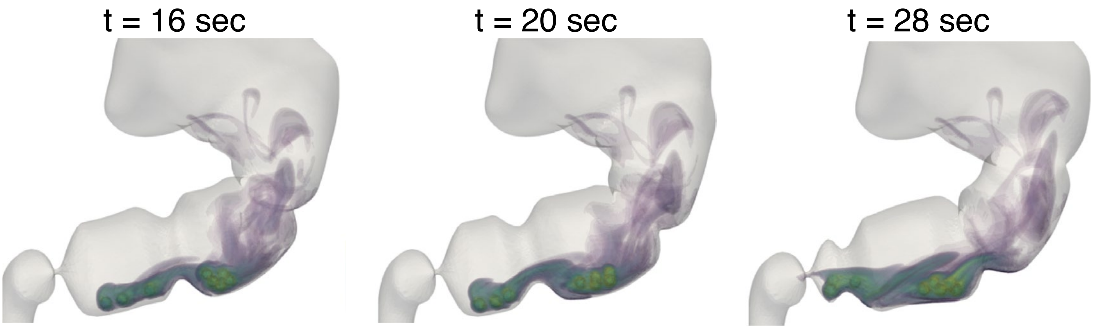

Figure 10: Simulating the erosion of solid food particles of size 4 mm via particle-resolved approach using an immersed boundary method-based solver.

particle-resolved approach. Spheres of diameter 4 mm were released in the upper stomach and they move under the action of gravitational and hydrodynamic forces (Fig. 10).

9 Conclusion

The physics of gastric digestion is driven by three equally important factors—stomach motility, multi-fluid/multiphase fluid dynamics, and gastric chemistry. Each component in this tripartite process opens up a large space of parameters and mechanisms. Motility may be affected by diabetes, Parkinson's disease, ageing, inflammation, or may be idiopathic in nature. Gastric fluid dynamics may involve liquid foods of different densities, viscosities, and nutritional content, as well as solid particles of different sizes. Digestive enzymes that break down food in the stomach have different pH activation profiles and act differently on proteins, fats, and carbohydrates. In recent times, computational modelling of the stomach has improved in fidelity and is starting to address some of these mechanisms.

The effect of changes in stomach motility on the contents of the stomach is the most studied phenomenon. Many studies have also investigated the effects of motility disorders. Changes in the gastric flow due to different viscosities of contents have also been explored by several studies. The multiphase nature of the contents and its effect on stomach function is mostly unexplored. The chemistry of the gastric phase of digestion has also received little attention. The consequences of surgery remain the least studied.

Accurate computational models also require information from in-vivo measurements, and lack of such measurements is also a stumbling block for computational models. The large variations in the motility measurements, enzyme secretion rates, and gastric emptying rates; and the shortage of particle-size distribution data and post-operative geometric measurements, all add to the challenge of developing clinically relevant computational models.

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Data availability

Data sharing is not applicable to this review article as no new data were created or analyzed.

Declarations

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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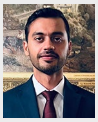

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