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Modelling and Simulation of Human Small Intestine

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1. Physical Phenomena of Duodenum

Duodenal Motility

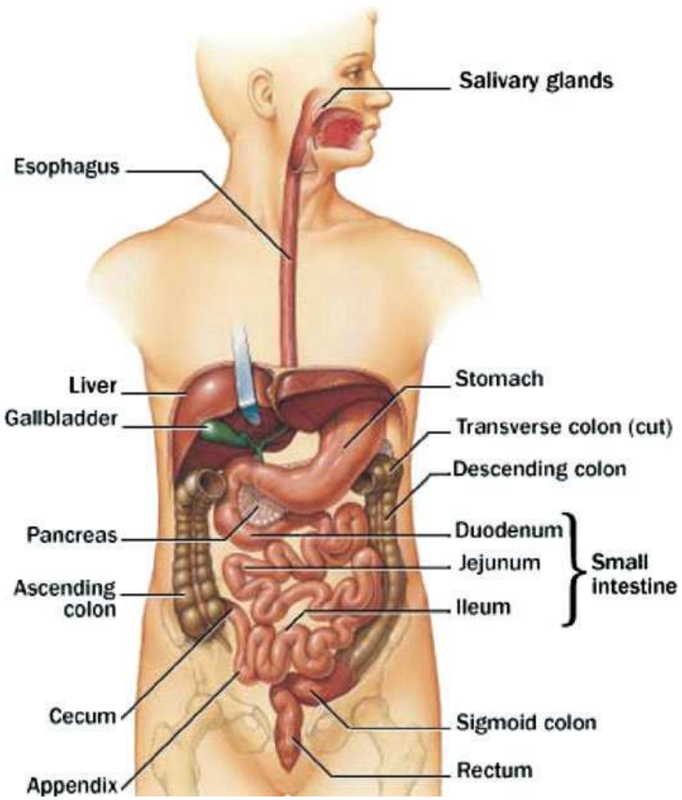

Figure 1: Gastrointestinal tract (Tharakan et at., 2010).

Two movements of small intestine and duodenum:

1. Peristalsis (promotes propulsion)
2. Segmentation (promotes mixing)

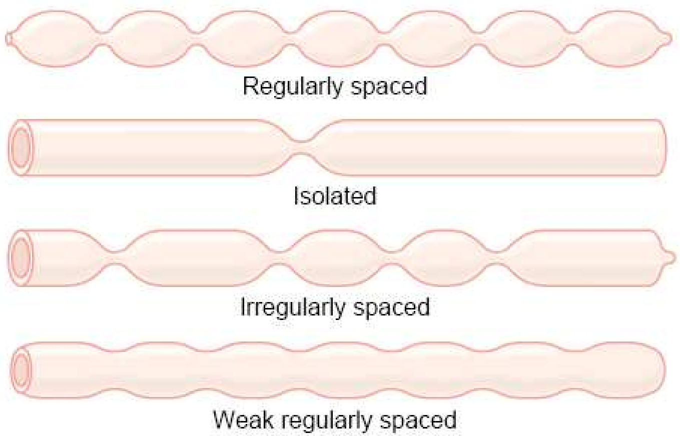

Figure 2: Duodenal motility (Guyton and Hall, 2010).

Duodenal Motility

Duodenum motility consists of:

•Segmentation, peristalsis, peristaltic rushes (powerful and rapid peristalsis) and reversed movements:

•Segmentation contractions mix (chop) digestive secretions from bile and pancreas with acidic chyme secreted from stomach, while peristalsis waves move chyme further to jejunum and ileum,

•Peristalsis waves move at a velocity of 2.0 cm/s to 0.5 cm/s, are weak and die after 3 cm to 5 cm, rarely 10 cm,

•Segmentation contractions are are very rare, they occur only 2 to 3 times/ minute, last only few seconds and travel only 1 cm.

2. *In-silico*
Dynamic Duodenum Model

CFD and FEA

An engineering tool, which helps engineers to understand and mimic fluid flow physical system is called **computational fluid dynamic** (**CFD**) technique. CFD is a branch of fluid mechanics that uses numerical methods to solve physical systems that involve fluid flows. Examples are flows in pipes, turbines, combustion engines, reactors, blood vessels or intestine. CFD software tools are ANSYS FLUENT, COMSOL Multiphysics, STAR-CD or ESI ACE+.

An engineering tool, which helps engineers to understand and mimic structural physical system is called **finite element analysis** (**FEA**) technique. FEA is a branch of solid mechanics that uses numerical methods to solve physical systems that involve structure and loads. Examples are deformation of cars, aircraft frames, loads of bridges or intestine walls. FEA software tools are ABAQUS, NASTRAN, COMSOL Multiphysics or ADINA.

CFD and FEA

Nowadays, CFD and FEA software tools are coupled into CFD Multiphysics software tools through fluid-structure interaction (FSI) coupling and thus useful for modelling more sophisticated real-life physical systems. CFD and FEA software tools are nowadays affordable and valuable in research and development departments in research organisations and industries:

1. Aerospace and defence

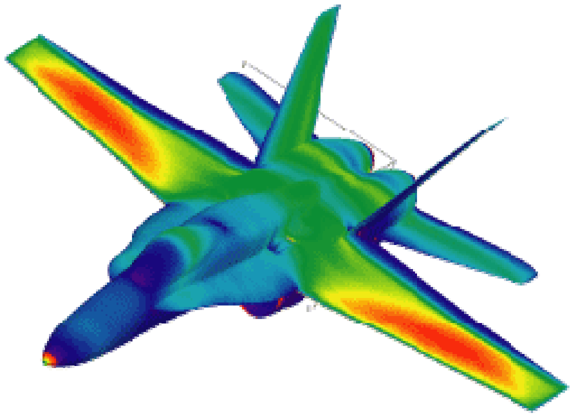

Figure 3: Airplaine (ANSYS, 2011).

2. Automotive

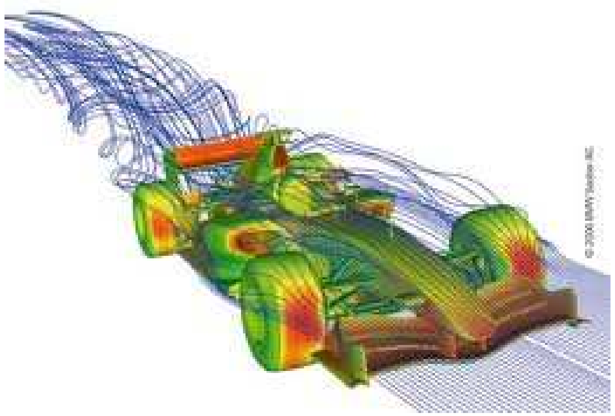

Figure 4: Formula 1 car (ANSYS, 2011).

CFD and FEA

3. Chemical and biochemical

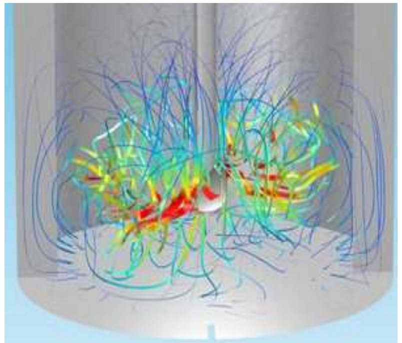

Figure 5: Reactor vessel (COMSOL, 2011).

4. Food and beverage

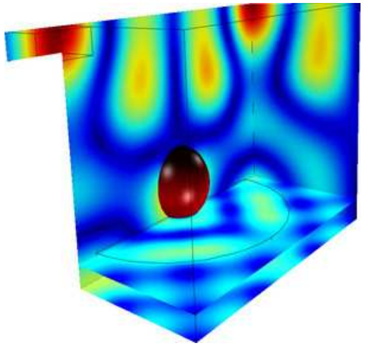

Figure 6: Microwave oven (COMSOL, 2011).

5. Biomechanics and biomedical

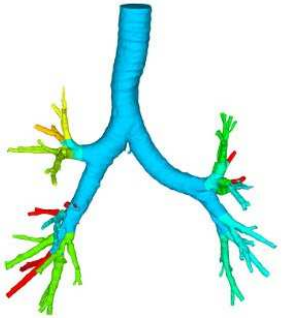

Figure 7: Blood vessel (ANSYS, 2011).

6. Electrochemistry and fuel cells

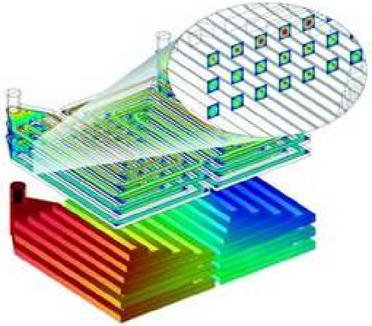

Figure 8: Fuel cells stack (COMSOL, 2011).

Some Existing *In-silico* Gastrointestinal Models

1. **Modelling the guinea pig ileum[3]**

2D CFD model study flow velocities, pressure, shear stresses and mixing generated by peristaltic movements in guinea pig ileum.

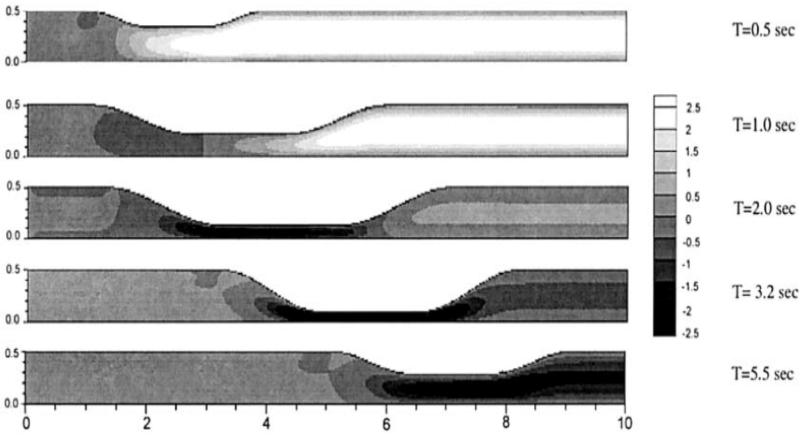

Figure 9: 2D CFD flow model of guinea pig ileum (Jefffey et al., 2003).

2. **Modelling the human stomach[4]**

2D CFD model, based on MRI images and lattice-Boltzmann equation, study contraction of stomach and mixing of gastric emptying.

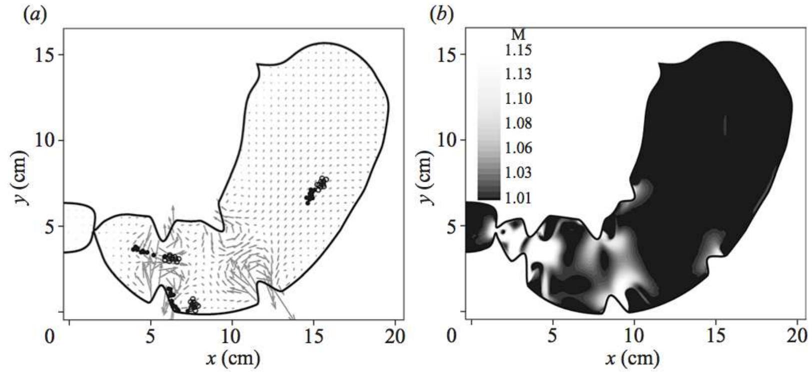

Figure 10: 2D CFD model of gastric mixing in human stomach (Pal et al., 2004).

Some Existing *In-silico* Gastrointestinal Models

3. **Modelling the human stomach[5]**

3D CFD model study contraction of stomach and characterise the fluid dynamics of gastric contents at different viscosities.

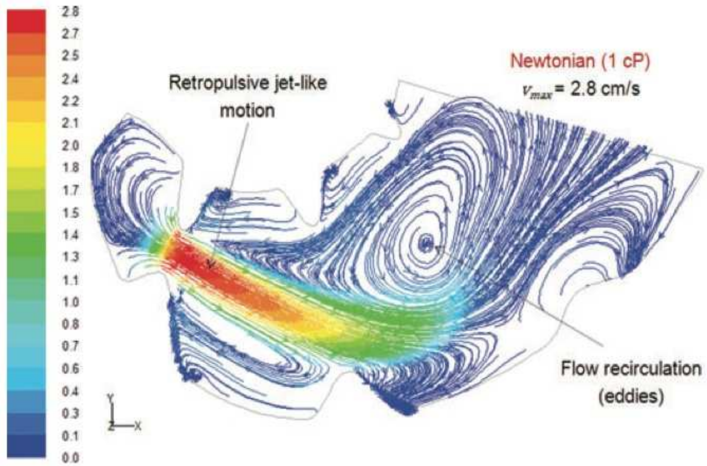

Figure 11: 3D model of human stomach (Ferrua and Singh, 2010).

4. **Modelling the nutrient absorption[6]**

2D multi-scale CFD model study nutrient absorption in villi based on micro scale lattice-Boltzmann model and macro scale fluid flow in the small intestine.

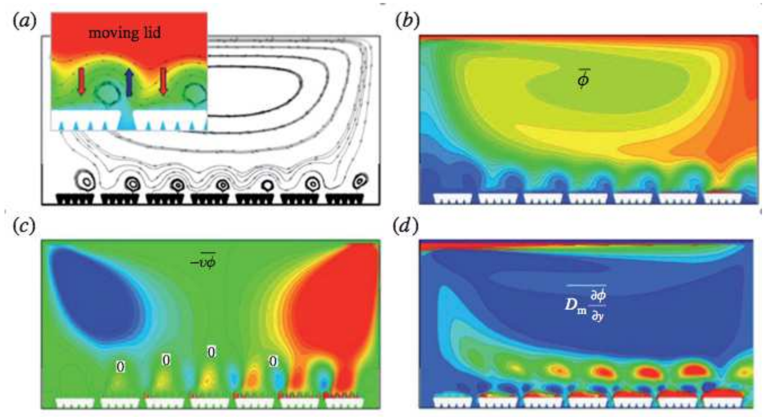

Figure 12: 2D multi-scale model of villi and the small intestine (Wang et al., 2010).

In-silico Dynamic Duodenum Model

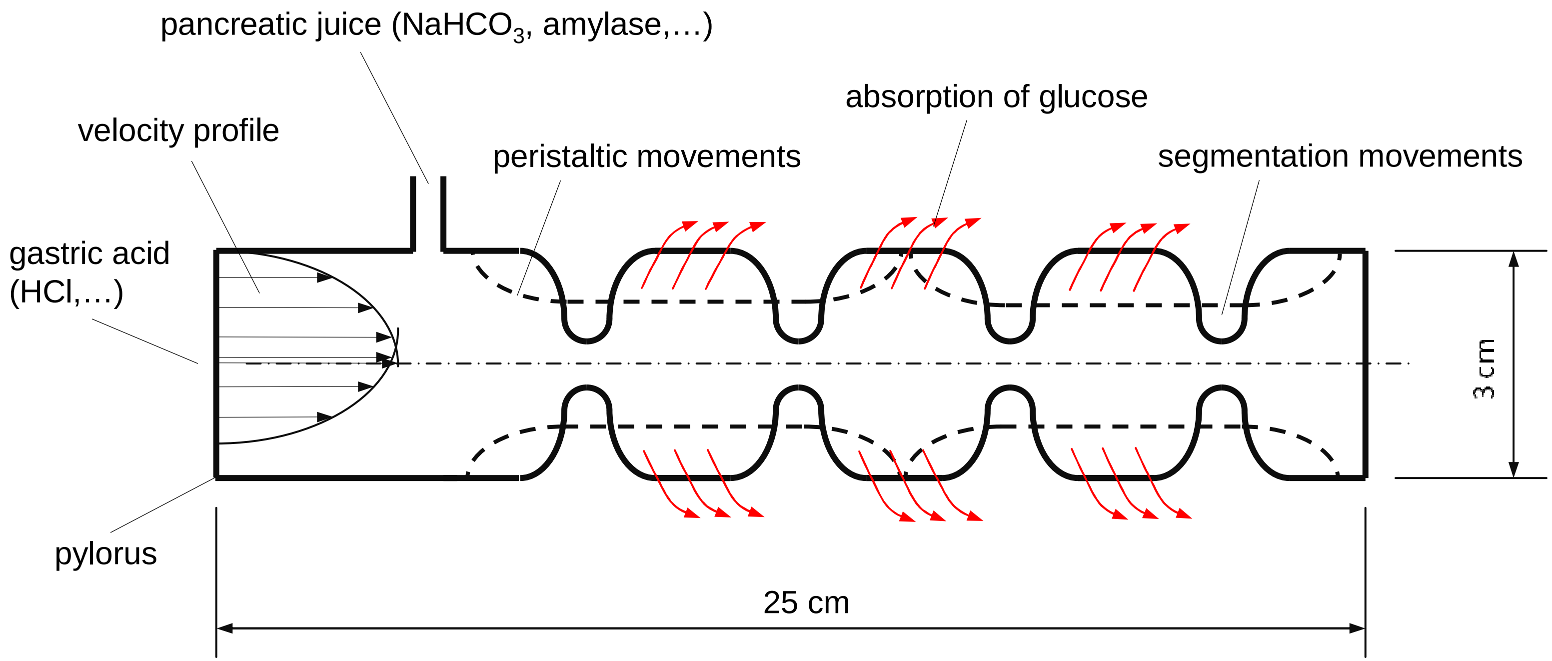

Figure 13: *In-silico* sketch of the Dynamic Duodenum Model.

In-silico Dynamic Duodenum Model

Modelling and simulation of duodenum consists of:

1. Modelling peristaltic and segmentation movements of duodenum solid wall (FEA solver),
2. Modelling fluid flow - chyme inside duodenum solid wall includes non-Newtonian flow, convective mixing and diffusion of nutrients(CFD solver),
3. Coupling solid and fluid mechanics solvers into fluid – structure interaction (FSI) model to get realistic results (CFD and FEA),
4. Modelling of biochemical reactions inside duodenum solid wall caused by reactions among gastric, bile and pancreatic secretions, such as hydrochloric acid, starch, sodium hydrogen carbonate and amylase.

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Preliminary *In-Silico* Results

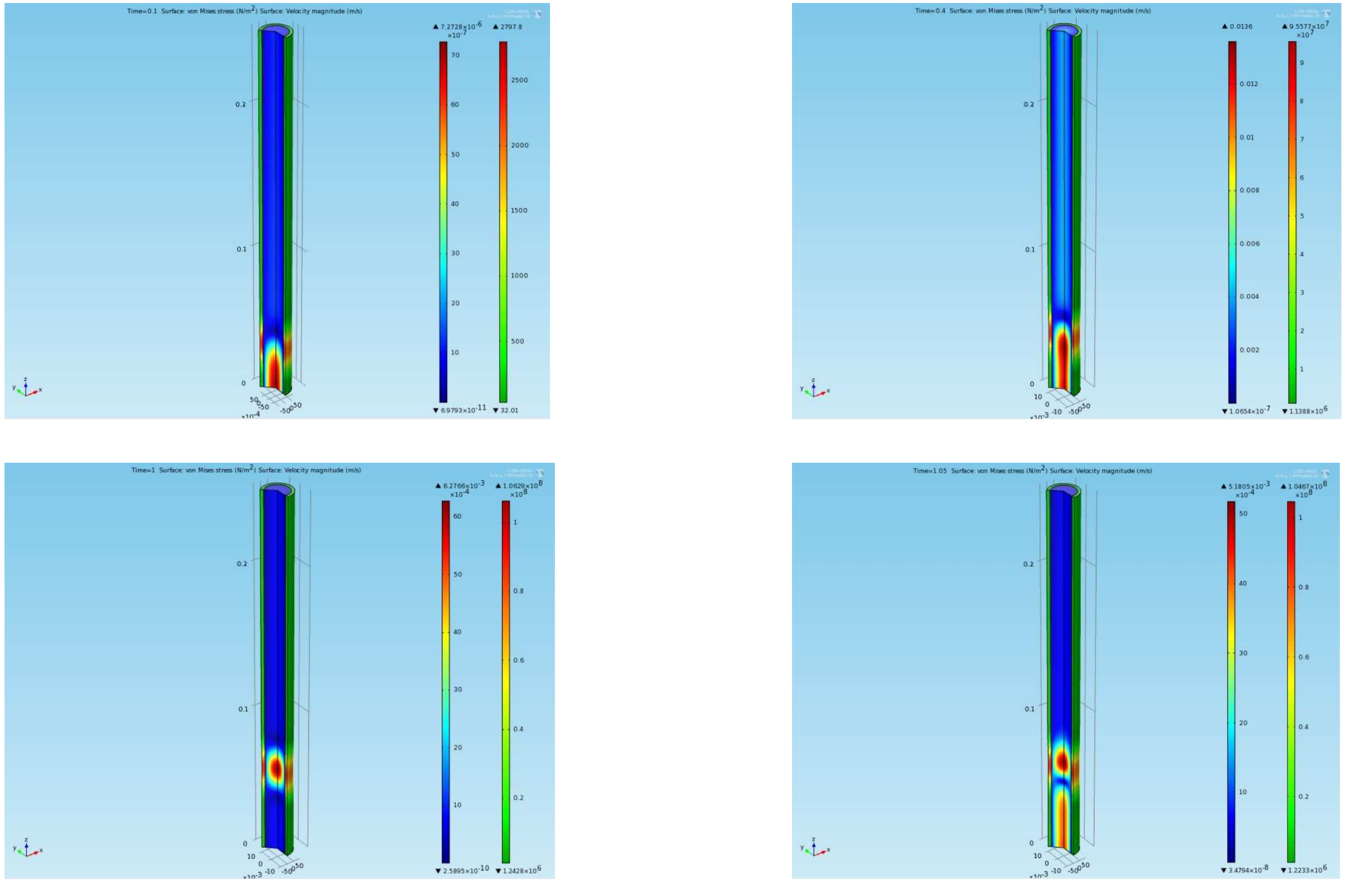

Figure 14: Fluid-structure interaction snapshots of a coupled duodenum wall and fluid flow inside duodenum. Snapshots represent von Misses stresses on the duodenum wall and velocity magnitude of chyme at different time steps t = 0.1 s, t = 0.4 s, t = 1.0 s, t = 1.05 s.

Preliminary *In-Silico* Results

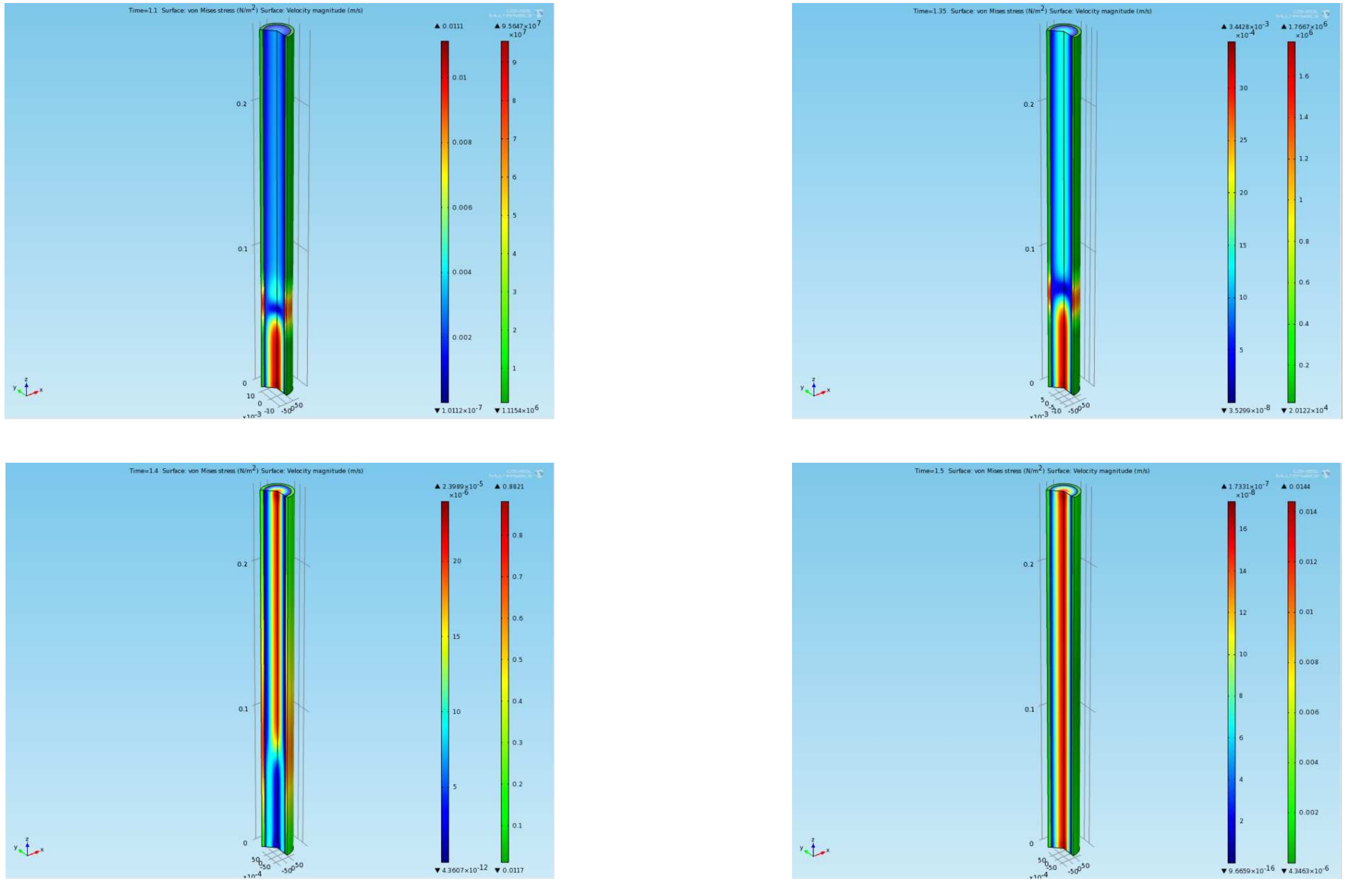

Figure 15: Fluid-structure interaction snapshots of a coupled duodenum wall and fluid flow inside duodenum. Snapshots represent von Misses stresses on the duodenum wall and velocity magnitude of chyme at different time steps t = 1.1 s, t = 1.35 s, t = 1.4 s, t = 1.5 s.

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3. *In-vitro*
Dynamic Duodenum Model

Some Existing *In-vitro* Gastrointestinal Models

1. Gastro-Intestinal Tract Model[7]

Dynamic computer controlled *in-vitro* system of human stomach and small intestine including peristalsis, but not segmentation.

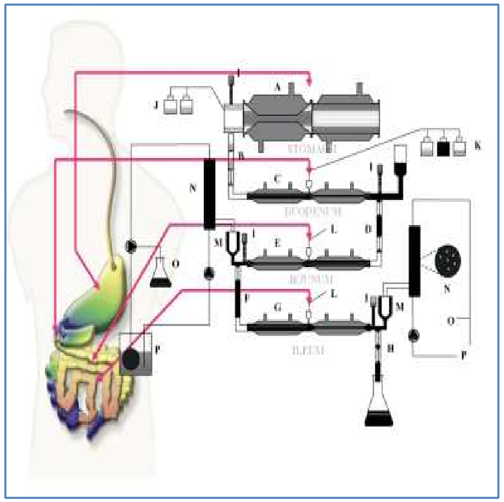

Figure 16: Gastro-Intestinal Tract Model (Netherlands Organisation for Applied Scientific Research, Zeist, Netherlands) (Blanquet et al., 2001).

2. Human Large Intestine Model[8]

Three-stage membrane model study concentration of bacteria, fatty acids and carbohydrates in the human large intestine without peristalsis and segmentation.

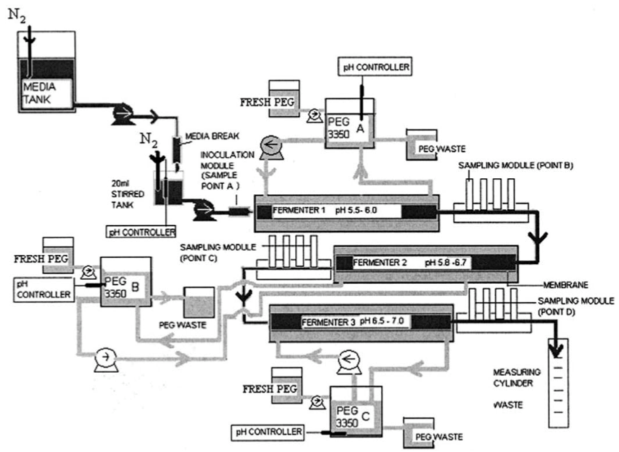

Figure 17: Three-stage large intestine model (Spratt et al., 2005).

Some Existing *In-vitro* Gastrointestinal Models

3. **Dynamics model of GI tract for the study of probiotics[9]**

Dynamic computer model simulates digestion and survival of microorganisms in stomach and duodenum consisting of two conventional CSTR reactors.

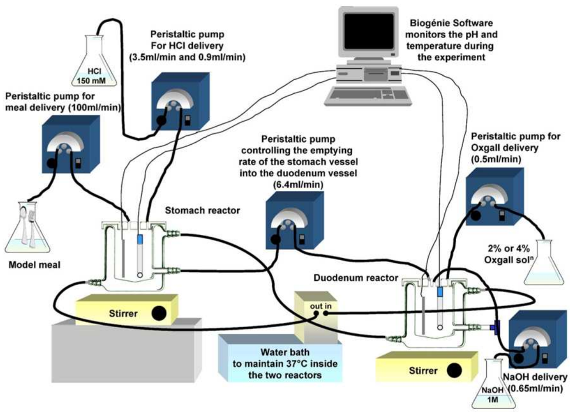

Figure 18: Dynamic *in-vitro* human stomach and duodenum model (Mainville et al., 2005).

4. **Model Gut[10]**

Dynamic computer controlled *in-vitro* system of human stomach that simulates human digestion.

Figure 19: Model Gut (Institute of Food Research, Norwich, UK) (Mercuri 2010).

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In-vitro Dynamic Duodenum Model

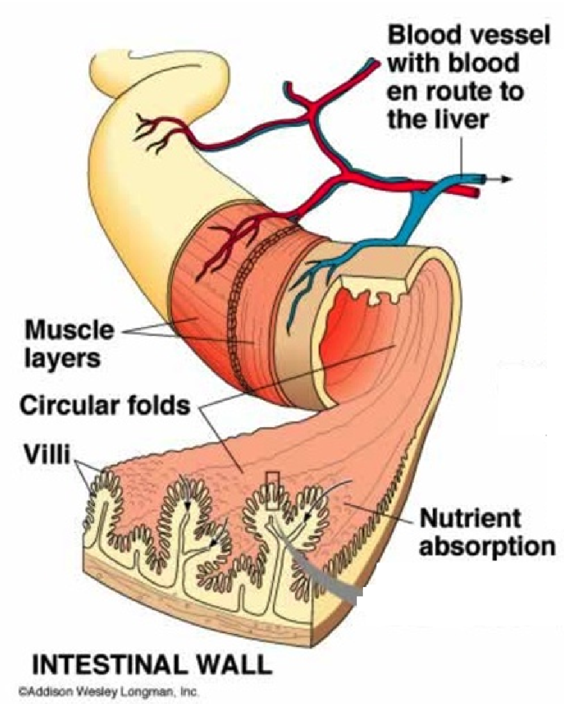

Figure 20: *In-vivo* intestine wall
(The Encyclopedia of Science, 2011).

Figure 21: *In-vitro* small intestine model.

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Literature

1. A. Tharakan, I.T. Norton, P.J. Fryer, S. Bakalis (2010): Mass transfer and nutrient absorption in a simulated model of small intestine. Journal of Food science, 75 (6), E339-E346.
2. A.C. Guyton, J.E. Hall (2010): Textbook of Medical Physiology, twelfth edition, Philadelphia: Saunders – Elsevier.
3. B. Jeffrey, H.S. Udaykumar, K.S. Schulze (2003): Flow fields generated by peristaltic reflex in isolated guinea pig ileum: impact of contraction depth and shoulders. American Journal of Physiology Gastrointestinal and Liver Physiology, 285: G907-G918.
4. A. Pal, K. Indireshkumar, W. Schwizer, B. Abrahamsson, M. Fried, J.G. Bracceur (2004): Gastric flow and mixing studied using computer simulation. Proceedings of the Royal Society B, 271: 2587-2594.
5. M.J. Ferrua, R.P. Singh (2010): Modeling the fluid dynamics in a human stomach to gain insight of food digestion. Journal of Food Science, 75 (7): R151-R162.
6. Y. Wang, J.G. Brasseur, G.G. Banco, A.G. Webb, A.C. Ailiani, T. Neuberger (2010): A multi-scale lattice Boltzmann model of macro- to micro-scale transport with applications to gut function. Philosophical Transactions of The Royal Society A, 368: 2863-2880.
7. S. Blanquet, S. Marol-Bonnin, E. Beyssac, D. Pompon, M. Renaud, M. Alric (2001): The ‘biodrug’ concept: an innovative approach to therapy. Trends in Biotechnology, 19 (10): 393-400.
8. P. Spratt, C. Nicolella, D.L. Pyle (2005): An engineering model of the human colon. Transactions of IChemE, Part C, 83 (C2): 147-157.
9. I. Mainville, Y. Arcand, E.R. Farnworth (2005): A dynamic model that simulates the human upper gastrointestinal tract for the study of probiotics. International Journal of Food Microbiology 99: 287-296.
10. A. Mercuri (2010): The dynamic gastric model: a new in vitro model for biorelevant dissolution and delivery assessment of oral dosage forms. UKICRS newsletter, 28-30.
11. The Encyclopedia of Science (2011): http://www.daviddarling.info/encyclopedia/S/small_intestine.html
12. ANSYS (2011): www.ansys.com.
13. COMSOL (2011): www.comsol.com.