Chapter 1

Introduction

Mathematical formulations of the laws of nature make them quantifiable. Such formulations are called mathematical models. They lay the fundamental and strong foundation for drawing useful inferences and pave the way for further research. Experimentations are immensely useful in studying the laws and draw conclusions, and also to validate mathematical formulations; but experiments are not always possible due to some limitations adhered to or the cost associated with. Hence, theoretically conceived or experimentally verified mathematical models are enormously useful. It is not only the physical or chemical sciences where mathematical models are constructed; biological and social sciences as well use mathematical models extensively. Even languages and literatures make use of models constructed mathematically. Biological models are quite advantageous in diagnosis and clinical treatments.

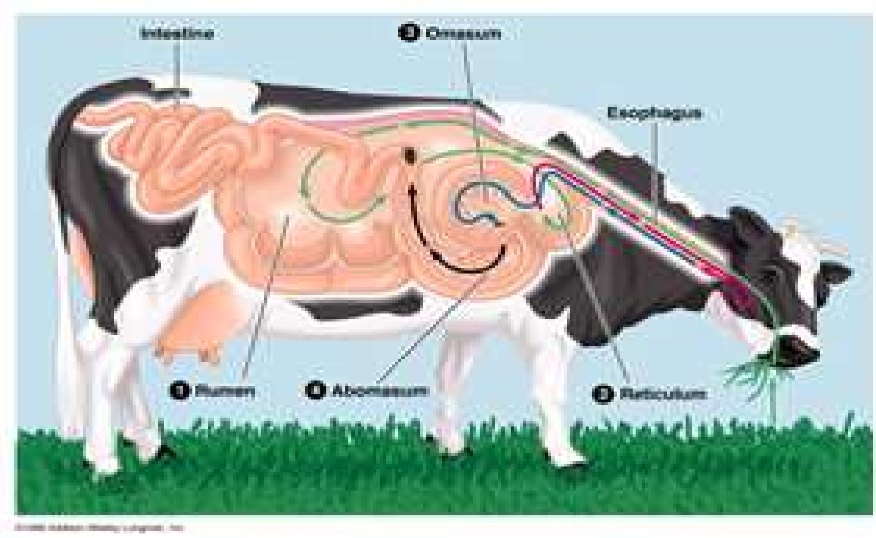

Figure 1.1: Swallowing and regurgitation of cow (Courtesy `https://www.futurelearn.com/info/courses/climate-smart-agriculture/0/steps/26577`)

1.1 Physiological systems associated with peristalsis

1.1.1 Oesophagus

Oesophagus is a 25 – 30 cm long muscular tube which connects pharynx to stomach (Lamb and Griffin, 2005). In an adult human, its diameter is 1.8 – 2.1 cm (Joohee *et al.*, 2012). It is a constituent of the digestive system (Fig. (1.3)). Swallowing in oesophagus is a rhythmic mechanism for transporting fluids or food boluses which are formed after chewing of food by teeth and are pushed through pharynx into oesophagus by means of tongue. This natural phenomenon of pumping does not require any pumping device such as piston. This protects food boluses from all sorts of possible pollutions and contaminations by the machinery. It further minimizes the use of lubricants.

Swallowing is accomplished by wave like motions of the oesophageal wall which is made up of longitudinal and circular muscles. Circular muscles contract the oesophagus when they become active, while longitudinal muscles stretch it to help regain its fully expanded tubular shape, called relaxation. Contraction and relaxation are periodic and beautifully coordinated actions. This typical pumping causes transportation of fluids also in the intestines and other parts of the body. We call it ***peristalsis***. It is caused by some electro-chemical reactions taking place in the body which activate circular and longitudinal muscles of the oesophagus. As a consequence, a progressive transverse wave like propagation is observed on its wall which transports the fluid lying within.

In addition to swallowing, oesophagus also restrains reflux of gastric contents but allows regurgitation, vomiting and belching. It is helped by upper and lower oesophageal sphincters appended to it at the proximal and distal ends. Any deficiency of oesophageal function can lead to dysphagia, gastro-oesophageal reflux or oesophageal pain.

The upper oesophageal sphincter regulates the passage of the masticated food bolus, while the lower oesophageal sphincter (i.e., cardiac sphincter) is an outlet to the abdomen for further dealing in the digestive system.

The upper oesophageal sphincter is made up of thick circular muscles to prevent reflux of oesophageal contents while the cardiac sphincteris made up of thick circular muscles in humans of an axial length of 2–4 cm. (Boeckxstaens, 2005).

The oesophageal flow is classified into primary peristalsis and secondary peristalsis (Paterson *et al.*, 1991, Mashimo and Goyal, 2006).

Primary peristalsis is referred to the mechanism of the movement of contraction waves from the pharynx to the cardiac sphincter along the oesophagus. Primary peristaltic is fastest in the proximal part and diminishes in the middle and the lower part of the oesophagus. On an average, primary peristalsis propagates at 4 cm/sec and it takes 10 – 15 seconds to complete its activity.

Secondary peristalsis is a mechanism activated by distention of oesophagus. It is restricted to oesophagus only. Sometimes food is seen as residue in the oesophagus owing to ineffective primary peristalsis or due to reflux from the stomach. This residual food is evacuated by secondary peristalsis. It is a local phenomenon which starts just above the point of distension and moves downward in the oesophagus.

1.1.2 Intestine

Intestine is a division of the digestive system (Fig. (1.3)). Absorption of nutrients and water takes place in intestine. In humans, it has two parts, viz., small and large intestines.

The small intestine is 7 meter long in an adult human and 2.5 – 3 cm in diameter. The small intestine is 1.5 meter long of diameter 7.5 cm and has subdivisions, namely, duodenum, jejunum and ileum. The large intestine is caecum and colon as subdivision. The colon absorbs water from the waste of the digestive food and creates transforms intoexcreta.

Peristaltic motion observed in physiological flows is categorizedas Rush peristalsis, anti- peristalsis and mass peristalsis (Wright *et al.*, 1982).

Rush peristalsis is ordinary peristalsis found in various physiological flows. This term is referred to primarily in the small intestine.

Anti-peristalsis acts in the direction opposite to the rush peristalsis. It propagates in the oral direction in the oesophagus and is observed in the second

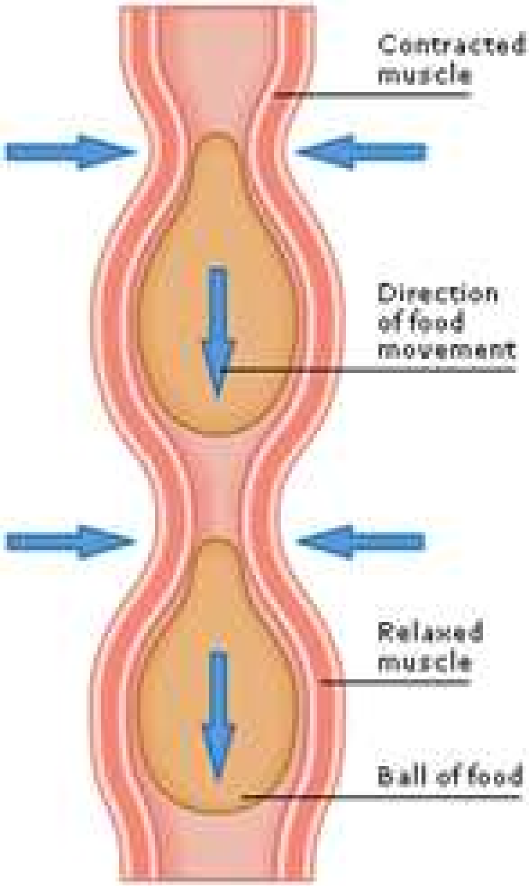

Figure 1.2: The peristaltic transport through oesophagus (Courtesy `http://kypho.com/deglutition.html`)

and third parts of the duodenum. Anti-peristaltic waves of contractions are also spotted in the oesophagus of birds and mammals forregurgitation of crop contents by mammals and feeding of nestlings and hatchlings (baby birds) of birds, Belching of gas formed in the stomach of ruminants and camelids (cf. Sellers and Stevens, 1960) and stomach of dogs (cf. Heywood and Wood, 1988) are also cases of anti-peristalsis.

Mass peristalsis is similar to the rush peristalsis and is the main pumping mechanism of the large intestine.

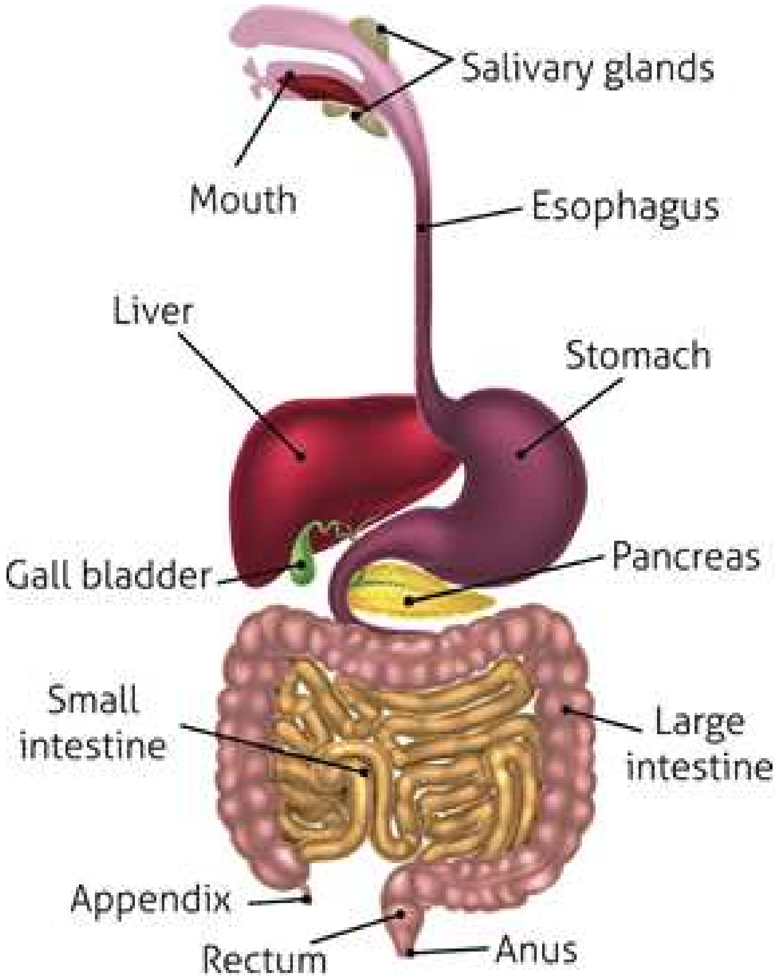

Figure 1.3: The digestive system (Courtesy https://www.pinterest.com/pin/361765782566604002/)

1.1.3 Ureter

Ureters are two in number. They aremuscular ducts of length 30 cm and diameter of 4 mm. They connect the kidneys to the bladder. Urine passes from the kidneys through ureters to the bladder.

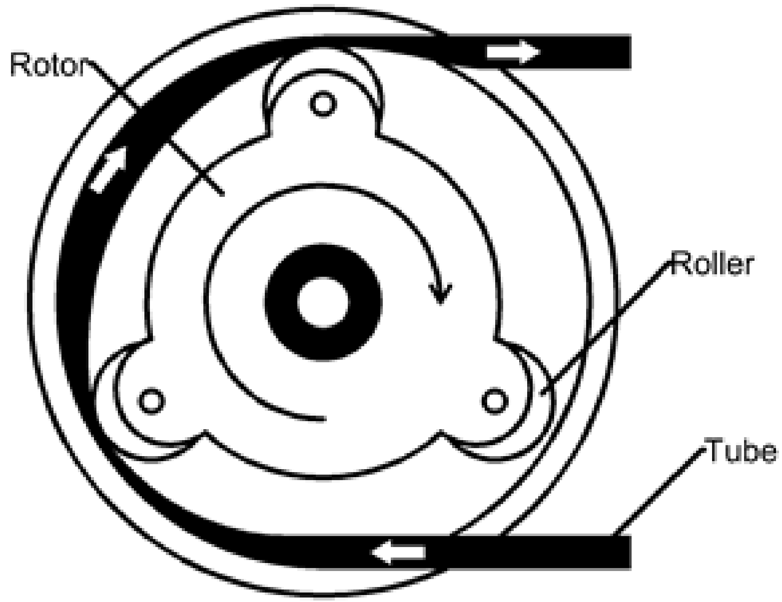

Figure 1.4: Peristaltic pump (Courtesy https://2018.igem.org/Team:Rotterdam_HR/Hardware_Peristaltic_Pump)

1.1.4 Vas deferens

The long muscular tube originating at the testes near epididymis and connecting to the ejaculatory duct carrying seminal fluid is called vas deferens. It is 45 cm long in an adult. The seminal fluid is carried from the vas deferens to the urethra.

1.2 Peristaltic pump

Peristaltic pump is a mechanical device and is based on the biological principle of peristalsis. It is used to pump fluids mechanically. It repeatedly expand a cavity to allow fluids to flow into the cavity and then seal that cavity. The pump works by compressing the flexible tube by rotating wheel which attaches adjustable fingers or rollers. There are several peristaltic pumps such as blood pump in heart lung machines (Fig. (1.4)), diabetic pump, roller pump etc.

1.3 Oesophageal diseases

1.3.1 Hiatus hernia

Diaphragm is dome shaped and separates the abdomen from the chest. Hiatus is a holein the diaphragm, which allows oesophagus to connect to the abdomen. Sometimes a part of the abdomen bulges up through the hiatus. This state is referred to as hiatus hernia (Fig. (1.5)). An accepted theory of origin is that intra-abdominal pressure increases above the normal to increase the normal gradient between intra-thoracic and intra-abdominal pressure. As a result, the oesophago-gastric junction is pressed up into the hiatus (Christensen and Miftakhov, 2000). Due to this bulging oesophagus diverges at the distal end or is a combination of divergence and convergence (Dushyant Kumar *et al.* (2020)).

Hiatus hernia causes heartburn but may also give chest pain or pain while eating. This state occurs in people over 50 years or have an unusual large hiatus at time of birth. Hiatus hernia may give symptoms of oesophageal reflux disease.

Sliding hiatus hernia and para-oesophageal hernia are the two kinds of hiatus hernia.

1.3.1.1 Sliding hiatus hernia

Sliding hiatus hernia is very common and is recognised as a significant axial prolapse of the stomach through the hiatus. It may slide up and down through the hiatus and is usually described as a separation, of 2 cm or more, of the upward displaced oesophago-gastric junction and diaphragmatic impression (Weyenberg,

Figure 1.5: Normal oesophagus and hiatus hernia (Courtesy: `https://www.msdmanuals.com/en-au/professional/gastrointestinal-disorders/esophageal-and-swallowing-disorders/hiatus-hernia`)

2013). Usually it doesn't lead to any serious symptoms and may not require treatment.

1.3.1.2 Para-oesophageal hiatus hernia

Para-oesophageal hiatus hernia is a serious condition. The abdominal cavity bulges up through the hiatus into the part of the thoracic cavity between the lungs and stucks. It is less common (5-15%) but may cause blockage of blood flow into stomach.

1.3.1.3 Symptoms of hiatus hernia

No symptoms are experienced by patients for the sliding hiatus hernia. However, sometimes it takes the form of heartburn and regurgitation when the stomach acid refluxes back into the oesophagus. However, some patients experience this chronic reflux of acid with fixed hiatus hernias. Hiatus hernia can intensify gastro-esophageal reflux.

The symptoms of hiatal hernia can look like many disorders. Therefore it is also called the ”great mimic”. The following symptoms can be experienced by a person with hiatus hernia, e.g., pains in the chest, shortness of breathing with heart palpitation, ingested food and causing discomfort in lower oesophagus until it passes on to stomach, several causes of acid reflux feeling sick, and mouth filling with saliva.

1.3.1.4 Cause of hiatus hernia

It is not often clear why this happens, but pressure on the stomach and age-related changes in diaphragm may be attributed to the formation of a hiatus hernia. A person may be born either with weak muscle tissues surrounding this opening. Persistent and intense pressure on the surrounding muscles due to vomiting, coughing, straining during a bowel movement or lifting heavy objects may lead to hiatus hernia.

Hiatus hernia may be caused by injury to the area, pushing up of the stomach by increased intra-abdominal pressure, pulling up of the stomach due to oesophageal shortening, obesity or pregnancy.

1.3.2 Gastro-oesophageal reflux disease

Abdominal contents are sometimes pushed back into the oesophagus. This is due to a disease called gastro-oesophageal reflux disease (GERD). GERD occurs frequently in an affected person. The number of patients suffering from this disease runs in millions. This is owing to weakness of the cardiac sphincter. Bile acid and pancreatic enzymes lying in the stomach sometimes regurgitate into the oesophagus and produce irritation in the oesophagus near the heart. It is called heartburn. Hiatus hernia causes GERD.

1.3.3 Barrett's oesophagus

When the normal cells lining the oesophagus change into an intestinal cell type, we call this condition Barrett's oesophagus. Such intestinal cells are generally precancerous. This lets gastric contents reflux into the oesophagus over time, and injures the normal squamous cells of the oesophagus. The chronic reflux disease and the presence of bile critically determine the formation of Barrett's oesophagus.

Biopsies and endoscopy detect Barrett's oesophagus. Although some visible clues may help diagnose the presence of the abnormal intestinal cells replacing the normal oesophagus, but biopsies confirm. The main treatment is controlling the reflux disease.

1.3.4 Achalasia

Achalasia is a state of dysfunction of the distal part of oesophagus. The lower oesophageal sphincter is a thick circular muscle layer of the distal oesophagus. The prime function of the lower oesophageal sphincter is to create a high-pressure and to relax for a short while to give way to ingested food. Achalasia hinders adequate lower oesophageal sphincter relaxation. As a consequence, oesophageal clearance is delayed. This causes a backup of food contents within oesophagus (Spechler and Castell, 2001).

Achalasia patients often feel that food is trapped in their oesophagus. Other symptoms may be pain or discomfort in chest and even heartburn. This is usually by autoimmune condition or heredity. Degeneration of nerves in oesophagus may pave the way to the advanced symptoms of achalasia. Drugs and operation are possible treatments for patients with inadequate lower oesophageal sphincter relaxation. Achalasia's treatment is dilation or surgical myotomy. Dilatation of achalasia is accomplished by complete disruption of the lower oesophageal sphincter.

1.3.5 Nutcracker oesophagus

Castell and his co-researchers named a dysfunction nutcracker oesophagus. It is a motility disorder having hypertensive contraction waves developed in the distal oesophagus during peristalsis (Spechler and Castell, 2001; Ladd *et al.*, 2013). Despite high amplitudes, these waves maintain peristaltic pattern. Nutcracker oesophagus is rare but gives rise to oesophageal food impaction. It is a differential diagnose of the non-achalasia motility disorders. The symptoms are chest pain and dysphagia. High-resolution manometry plays a key role to diagnose nutcracker oesophagus.

1.3.6 Oesophageal cancer

Oesophageal cancer takes place when the oesophageal cells are abnormal and function improperly. The abnormal cells grow and increase abnormal cells in number. Squamous cell carcinoma and adenocarcinoma are ninety-five per cent of oesophageal cancer. First one is rooted in the mucosa layer and second one grows in sub-mucosa layer of the oesophagus. However, cancerous cells may be seen anywhere in the oesophagus.

1.3.6.1 Signs and symptoms of oesophageal cancer

A patient of oesophageal cancer shows symptoms like painful swallowing, heart-burn and indigestion, retrograde food flow, coughing up blood, weight loss, sticking of food in throat or chest, discomfort in the back, etc.

1.3.6.2 Treatment options of oesophageal cancer

Treatment of oesophageal cancer type and stage-dependent. Treatment is either to cure or to control. Treatments include surgery, chemotherapy, radiotherapy, cryosurgery or the combination of some of these.

1.4 Characteristic of physiological fluids

Physiological fluids such as blood, food stuffs, drilling mud, mayonnaise, tooth-paste, some lubricants, and nuclear fuel slurries are visco-plastic fluids (cf. Barnes, 1997). Further semi-fluids such as jelly, tomato puree, honey, soup, and concentrated fruits juices etc are highly concentrated and resemble Casson fluid in nature (cf. Barnes, 1997) are also of viscoelastic nature. Blood, chyme, polymer solutions, colloidal solutions, drilling fluids in oil industries are similar to micro-polar fluid. Besides, some edible solutions are also micro-polar. Food materials such as solutions of roasted cereal powders consumed in Indian subcontinent may be viewed as micro-polar fluid. Plasma (blood), liquid metals and salt or sea water are magneto-hydrodynamic. The couple stress model plays an important role in understanding some of the non-Newtonian flow properties of colloidal fluids, liquid crystals, some food materials, blood (human and animal). Investigation of peristaltic transport of such non-Newtonian fluids is useful for understanding the flow patterns of masticated food stuff in the oesophagus.

Stomach churns the food and mixes with gastric acid. Semi-digested food mixed with stomach acids is called chyme. In the small intestine, bile, pancreatic enzymes and other digestive enzymes produced by the inner wall of the small intestine help to breakdown food. This chyme flowing in the intestines is more or less of vico-elastic, of Casson type , or of micro-polar nature.

1.5 Hypothesis of the research

The present thesis deals with the flow dynamics of oesophageal swallowing in normal and pathological states. Kahrilas *et al.* (1995) published a report based on their experiments on healthy and non-healthy persons, which had discovered higher pressure in the distal part of the oesophagus than that in the pharyngeal part. Meanwhile Xia *et al.* (2009) submitted an anatomical report on oesophagus during swallowing. Pandey *et al.* (2017) analysed the two reports, concluded that the wavelength of the peristaltic waves increase progressively during swallowing to drag food boluses that gradually get globular. They also presented a mathematical model for swallowing of Newtonian fluids.

Since swallowing in oesophagus is managed by progressive peristaltic waves which not only drag the fluid within the oesophagus but also create more pressure in the distal part, therefore an appropriate wall equation, which was developed by Pandey *et al.* (2017), has been considered for analyses. Such peristaltic waves have amplitudes that increase as the waves progress and finally create higher pressure in the distal part.

The food we consume is masticated in the mouth and mixed with saliva. Thus it transforms itself into a semi-fluid which is put inside the oesophagus by means of the tongue. Therefore, the fluid has been considered as non-Newtonian nature or with particulate suspension. There are models for swallowing in the normal oesophagus under the influence of dilating peristaltic waves by considering the fluid as Newtonian [Pandey *et al.* 2017] and non-Newtonian [Pandey and Tiwari, 2017; Pandey and Singh, 2018]. However, the non-Newtonian nature of micro-polar type was left untouched. Therefore, fluids with non-Newtonian micro-polar properties have been considered for investigating the flow dynamics of swallowing in oesophagus. The analysis for micro-polar fluid is presented in Chapter 3 while Chapter 4 contains an equivalent analysis for particulate suspension in a Newtonian fluid. These analyses are useful when the oesophagus is normal.

Oesophagus is, however, not always normal. Sometimes it suffers from some dysfunctions. Hiatus hernia, described earlier in detail in the Introduction of the thesis, is such a dysfunction which gives adverse impacts on swallowing. Circumstances are thus changed. The oesophagus does not remain uniform. For this reason, we analyse swallowing in circular cylindrical tube which diverges or converges, not necessarily from the beginning because herniation of oesophagus affects it near the lower end. The geometry of the oesophagus becomes uneven. The non-uniformity may be linear or non-linear. Therefore, in Chapter 5, linear divergence of the tube and in Chapter 6, non-linear divergence is considered. The fluid considered is micro-polar in both the chapters. Chapter 7, deals with particulate suspension in a Newtonian fluid medium while non-uniformity is assumed to be non-linear. The detailed discussions are given in the introduction of the chapters. The conclusions drawn are quite useful and can help clinicians diagnose the dysfunction and prescribe remedial measures.

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