CHAPTER-I

GENERAL INTRODUCTION
1. PERISTALSIS

The word peristalsis stems from the Greek word Peristaltikos, which means clasping and compressing. Peristaltic pumping is a form of fluid transport generated in the fluid contained in a distensible tube when a progressive wave travels along the wall of the tube. It is an inherent property of many syncytial smooth muscle tubes; stimulation at any point can cause a contractile ring to appear in the circular muscle of the gut, and this ring then spreads along the tube. In such a way, peristalsis occurs in the gastrointestinal tract, the bile ducts, other glandular ducts throughout the body, the ureters, and many other smooth muscle tubes of the body (Guyton and Hall, 2003). Peristaltic pumping also has engineering applications, e.g. in situations where it is desirable to prevent the mechanical parts of the pump from coming into contact with a corrosive fluid.

2. PHYSIOLOGICAL SYSTEMS ASSOCIATED WITH PERISTALSIS

2.1 GASTROINTESTINAL TRACT

Two types of movements occur in the gastrointestinal tract: (1) Propulsive movements, which cause food to move forward along the tract at an appropriate rate to accommodate digestion and absorption and (2) mixing movements, which keep the intestinal contents thoroughly mixed at all times.

Propulsive Movements - Peristalsis

The basic propulsive movement of the gastrointestinal tract is peristalsis, which is illustrated in Fig. 1. A contractile ring appears around the gut and then moves forward; this is analogous to putting one’s fingers around a thin distended tube, then constricting the fingers and sliding them forward along the tube. Any material in front of the contractile ring is moved forward.
Mixing Movements

The mixing movements are quite different in different parts of the alimentary tract. In some areas, the peristaltic contractions themselves cause most of the mixing. This is especially true when forward progression of the intestinal contents is blocked by a sphincter, so that a peristaltic wave can then only churn the intestinal contents, rather than propelling them forward.

![Peristaltic contraction diagram](image)

**Fig. 1 Peristalsis**

2.2 ESOPHAGUS

The esophagus normally exhibits two types of peristaltic movements: primary peristalsis and secondary peristalsis. Primary peristalsis is simply a continuation of the peristaltic wave that begins in the pharynx and spreads into the esophagus during the pharyngeal stage of swallowing. This wave passes all the way from the pharynx to the stomach in about 8 to 10 seconds. Food swallowed by a person who is in the upright position is usually transmitted to the lower end of the esophagus even more rapidly than the peristaltic wave itself, in about 5 to 8 seconds, because of the additional effect of gravity pulling the food downward. If the primary peristaltic wave fails to move into the stomach all the food that has
entered the esophagus, secondary peristaltic waves result from the distention of
the esophagus by the retained food, and these waves continue until all the food
has emptied into the stomach. These secondary waves are initiated partly by
intrinsic neural circuits in the myenteric nervous system and partly by reflexes that
begin in the pharynx, then are transmitted upward through vagal afferent fibers to
the medulla and then back again to the esophagus through glossopharyngeal and
vagal efferent nerve fibers.

2.3 SMALL INTESTINE

Chyme is propelled through the small intestine by peristaltic waves. These
can occur in any part of the small intestine, and they move analward at a velocity
of 0.5 to 2.0 cm/sec, much faster in the proximal intestine and much slower in the
terminal intestine. They normally are very weak and usually die out after
travelling only 3 to 5 centimeters, very rarely farther than 10 centimeters, so that
forward movement of the chyme is very slow, so slow in fact that net movement
along the small intestine normally averages only 1 cm/min.

The function of the peristaltic waves in the small intestine is not only to
cause progression of the chyme toward the ileocecal value but also to spread out
the chyme along the intestinal mucosa. As the chyme enters the intestine from the
stomach and causes initial distention of the proximal intestine, the elicited
peristaltic waves begin immediately to spread the chyme along the intestine; this
process intensifies as additional chyme enters the duodenum.

Peristaltic Rush

Although peristalsis in the small intestine is normally very weak, intense
irritation of the intestinal mucosa, as occurs in some severe cases of infectious
diarrhea, can cause both powerful and rapid peristalsis, called the peristaltic rush.
This is initiated partly by nervous reflexes that involve the autonomic nervous
system and the brain stem and partly by intrinsic enhancement of the myenteric
plexus reflexes within the gut wall itself. The powerful peristaltic contractions travel long distances in the small intestine within minutes, sweeping the contents of the intestine into the colon and thereby relieving the small intestine of irritative chyme and excessive distention.

2.4 LARGE INTESTINE


Rhythmic variations of tone

This takes place throughout the large intestine but not always and is not at all concerned with propulsion; it rather maintains adequate circulation through the wall and helps in the absorption of water.

Peristalsis

Peristalsis is not equivalent as rush peristalsis seen in the small intestine. It is a weak peristalsis alternately shortening and elongating in the transverse colon.

Mass peristalsis

A movement is a modified type of peristalsis characterized by the following sequence of events: First, a constrictive ring occurs in response to a distended or irritated point in the colon, usually in the transverse colon. Then, rapidly thereafter the 20 or more centimeters colon distal to the constriction lose their haustrations and instead contract as a unit, forcing the fecal material in this segment en masse further down the colon. The contractions develop progressively more force for about 30 seconds, and relaxation and then occurs during the next 2-3 minutes. Then, another mass movement occurs, this time perhaps farther along the colon.
Anti-peristalsis

In the early stages of excessive gastrointestinal irritation, anti-peristalsis begins to occur often many minutes before vomiting appears. The anti-peristalsis may begin as far down in the intestinal tract as the ileum, and the anti-peristaltic wave travels backward up the intestine at a rate of 2-3 cm/sec; this process can actually push a large share of the intestinal contents all the way back to the duodenum and stomach within 3-5 minutes. Then, as these upper portions of the gastrointestinal tract, especially the duodenum, become overly distended, this destination becomes the exiting factor that initiates the actual vomiting act. In man it is rarely seen but is well marked in animals such as cat.

2.5 RENAL SYSTEM

Ureters

The ureters propel the urine from the kidneys into the bladder by peristaltic contraction of smooth muscle layer. This is an intrinsic property of the smooth muscle and is not under autonomic nerve control. The waves of contraction originate in a pacemaker in the minor calyces. Peristaltic waves occur several times per minute, increasing in frequencies with the volume of urine produced, and send little spurts of urine into the bladder.

2.6 REPRODUCTIVE SYSTEM

Fallopian tubes

The uterine tubes are about 10 cm long and extend from the sides of the uterus between the body and the fundus. They lie in the upper free border of the broad ligament and their trumpet-shaped lateral ends penetrate the posterior wall, opening into the peritoneal cavity close to the ovaries. The end of each tube has finger like projections called fimbriae. The longest of these is the ovarian fimbriae, which is in close association with ovary. The uterine tubes (fallopian
tubes) convey the ovum from the ovary to the uterus by peristalsis and ciliary movements.

3. CLASSIFICATION OF FLUIDS

1. Newtonian Fluid

If shear stress is linearly proportional to the rate of strain, the fluid is called as a Newtonian fluid. Newtonian behaviour has been observed in all gases, in liquids or solutions of materials of low molecular weight.

The constitute equation for Newtonian fluid is

\[ \tau = \mu \dot{\gamma} \]

where \( \tau \) is the stress, \( \dot{\gamma} \) is the shear rate and \( \mu \) is the viscosity of the fluid.

2. Non-Newtonian Fluid

Non-Newtonian fluids generally exhibit a nonlinear relationship between the shear stress and the rate of strain. Foodstuffs (like banana juice, apple juice, chyme), blood, slurries, sperm, intra uterine fluid, etc, behave like non-Newtonian fluids.

In this thesis an attempt is made to study the following non-Newtonian fluids:

(a) Jeffrey Fluid

The Jeffrey model is relatively simpler linear model using time derivatives instead of convected derivatives, for example Oldroyd-B model does; it represents a rheology different from the Newtonian.

The constitute equation for the Jeffrey fluid is

\[ \tau = \frac{\mu}{1 + \lambda_2 \dot{\gamma}} (\dot{\gamma} + \lambda_1 \dot{\gamma}) \]
where $\mu$ is the dynamic viscosity of the fluid, $\dot{\gamma}$ is the shear rate, $\lambda_1$ is the ratio of relaxation time to retardation time and $\lambda_2$ is the retardation time and dots over the quantities denote differentiation with respect to time.

(b) Carreau Fluid

The Carreau fluid model is a four parameter model and has useful properties of a truncated power-law model that does not have a discontinuous first derivative. It possesses shear thinning, i.e., the viscosity decreases by increasing shear rate, some time reaching to $10^{-3}$ or $10^{-4}$ for a zero shear rate.

The constitute equation for a Carreau fluid [following Bird et al. (1977)] is

$$
\tau = \left[ \eta_\infty + (\eta_0 - \eta_\infty) \left(1 + (1/\dot{\gamma})^{\lambda_2} \right)^{\lambda_1} \right] \dot{\gamma}
$$

where $\tau$ is the extra stress tensor, $\eta_\infty$ is the infinite shear rate viscosity, $\eta_0$ is the zero shear rate viscosity, $\Gamma$ is the time constant, $n$ is the dimensionless power-law index and $\dot{\gamma}$ is defined as

$$
\dot{\gamma} = \sqrt{\frac{1}{2} \sum_i \sum_j \dot{\gamma}_{ij} \dot{\gamma}_{ij}} = \sqrt{\frac{1}{2} \pi}
$$

where $\pi$ is the second invariant of strain-rate tensor.

(c) Third Order Fluid

Third order fluid behaves like a non-Newtonian fluid. Its viscosity and all other material parameters (non-Newtonian coefficients) are taken constants. These material parameters of third order fluid appropriate to shear thinning.

The constitute equation for the third order fluid is

$$
\bar{S} = \mu \bar{A} + \alpha_1 \bar{A}_1^2 + \beta_1 (\bar{A}_1 \bar{A}_1 + \bar{A}_1 \bar{A}_1) + \beta_2 (\tau \bar{A}_1^2) \bar{A}_1
$$

where $\mu$ is the viscosity, $\alpha_1, \alpha_2, \beta_1, \beta_2, \beta_3$ are the material constants and the Rivlin-Ericksen tensors ($\bar{A}_n$) are given through the following relations.
\[ \bar{A}_n = \left( \text{grad} \bar{V} \right) + \left( \text{grad} \bar{V} \right)^T \]

\[ \bar{A}_n = \frac{d}{dt} \bar{A}_{n-1} + \bar{A}_{n-1} \left( \text{grad} \bar{V} \right) + \left( \text{grad} \bar{V} \right)^T \bar{A}_{n-1}, \quad n > 1 \]

where \( \frac{d}{dt} \) is material derivative, \( \bar{V} \) is the velocity and \( T \) is the superscript denotes the transpose.

(d) Fourth Grade Fluid.

Fourth grade fluid behaves like a non-Newtonian fluid. Its viscosity and all other material parameters (non-Newtonian coefficients) are taken constants.

The constitutive equation for the fourth grade fluid is

\[ S = \mu \bar{A}_1 + \alpha_1 \bar{A}_1 + \alpha_2 \bar{A}_1^T + \beta_1 \bar{A}_1 + \beta_2 (\bar{A}_1 \bar{A}_1 + \bar{A}_1 \bar{A}_1) + \beta_3 (\text{tr} \bar{A}_1) \bar{A}_1 \]

\[ + \gamma_1 \bar{A}_1 + \gamma_2 (\bar{A}_1 \bar{A}_1 + \bar{A}_1 \bar{A}_1) + \gamma_3 \bar{A}_1^2 + \gamma_4 (\bar{A}_1 \bar{A}_1 + \bar{A}_1 \bar{A}_1) + \gamma_5 (\text{tr} \bar{A}_1) \bar{A}_1 \]

\[ + \gamma_6 (\text{tr} \bar{A}_1) \bar{A}_1^2 + \left[ \gamma_7 \text{tr} \bar{A}_1 + \gamma_8 (\text{tr} \bar{A}_1) \right] \bar{A}_1, \]

where \( \mu, \alpha_1, \alpha_2, \beta_1, \beta_2, \beta_3, \gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7, \gamma_8 \) being material constants and \( \bar{A}_n \) representing the Rivlin – Ericksen tensors defined by

\[ \bar{A}_{n+1} = \frac{d\bar{A}_n}{dt} + \bar{A}_n \left( \text{grad} \bar{V} \right) + \left( \text{grad} \bar{V} \right)^T \bar{A}_{n-1}, \quad n > 1, \]

\[ \bar{A}_1 = \left( \text{grad} \bar{V} \right) + \left( \text{grad} \bar{V} \right)^T. \]

where \( \frac{d}{dt} \) is material derivative, \( \bar{V} \) is the velocity and \( T \) is the superscript denotes the transpose.

4. A BRIEF SURVEY OF LITERATURE

The problem posed by the coupling of moving walls with an enclosed fluid is difficult. Still, much progress has been made during the past 45 years in understanding the fluid dynamics of peristalsis. This progress has come from experimental, analytical and numerical work. In the analytical work, various simplifying assumptions have been made: zero Reynolds (Re) number, small-
amplitude waves, infinite wavelength, symmetric walls etc. (Burns and Parkes, 1967; Childress, 1981; Fing and Yih, 1968; Hanin, 1968; Jaffrin and Shapiro, 1971; Jaffrin, 1973; Shapiro et al., 1969). The numerical work has been less restrictive (Pozrikidis, 1987; Takabatake and Ayukawa, 1982; Takabatake et al., 1988). However, all previous analytical and numerical studies of peristaltic transport have examined the flux of fluid particles of zero area. Experimentally, Hùng and Brown (1976) studied the motion of a suspended particle due to the passage of a peristaltic wave. Their apparatus produced a two-dimensional peristaltic flow. They obtained qualitative results on how particle motion depends upon Re and wave parameters.

The fluid mechanics of the ureter form a lubrication theory point of view has been discussed by Lykoudis and Roos (1970). They studied the problem for arbitrary wave shapes and determined the minimum and maximum pressure in a tube with the wall whose displacements vary according to a power-law in the axial direction. Manton (1975) extended their approach to investigate some general properties of peristalsis and he accounted in his asymptotic expansion, for the inertia and viscous effects to an extent greater than that considered by Lykoudis and Roos (1970). The segmental wall contraction was reported by Lew et al. (1971), leading to the exploration of flow characteristics in the intestine. The peristaltic flow in a tapered channel and tube was first investigation by Gupta and Seshadri (1976). Following their analysis many other peristaltic flow problems are reported by Srivastava et al. (1983) and Mekheimer (2002). An asymptotic theory for the peristaltic transport in a flexible tube of arbitrary cross section has been developed by Shen (1976). He presented the velocity components for an elliptic tube, under small and finite amplitude assumptions. The influence of waveform on peristaltic transport of a Newtonian fluid was examined by Mahrenholtz et al. (1978) for high Reynolds number in a highly occluded channel. The peristaltic flow due to the propagation of lateral bending waves along the
channel walls has been investigated by Wilson and Panton (1979) and Wilson et al. (1979). Rath (1982) was investigated the peristaltic flow through a lobe-shaped tube under zero Reynolds number and long-wave length approximations. Hason et al. (1984) discussed the peristaltic pumping in three different waveforms, namely triangular, trapezoidal and square wave, with the applications to the flow of spermatic fluid in human vas deferens and that of rhesus monkey. The peristaltic transport in a tapered tube using the perturbation analysis with small amplitude has been studied by Misra and Pandey (1995). Usha and Ramachandra Rao (1995) have studied the peristaltic transport of a biofluid in a pipe of elliptic cross section. The single wave peristaltic flow of tear-drop shape was investigated by Tadjfar et al. (2000).

Over the past four decades many studies have appeared on peristaltic pumping. The particulate flows under peristalsis started as a matter of interest with the work of Hung Brown (1976). They have studied the non-linear peristaltic flow in which a particle is pumped with the fluid. Theoretically, the peristaltic flow with uniformly distributed suspended particles under low Reynolds number and long-wavelength assumptions were explained by Kaimal (1978). The corresponding particle fluid suspension problem in the two-dimensional planar channel has been discussed by Mekheimer (1998). Wilson and Perel (1979) studied interaction of pulsatile and peristaltic induced flows with the small amplitude expansion for a two-dimensional flow and the corresponding axisymmetric flow was studied by Srivastava and Srivastava (1985). Usha and Prema (1998) extended this theoretical analysis with the particle-fluid suspension. Following their analysis Usha and Prema (1998) have discussed the interaction of pulsatile and peristaltic transport induced flows of particle-fluid suspension. Peristaltic transport of a fluid-particle mixture has been investigated by Shen et al. (1981). A perturbation solution for peristaltic flow of a fluid-particle mixture for small amplitudes and arbitrary Reynolds number and wave
number was given by Srivastava & Srivastava (1989) and Misra and Pandey (1994). Srivastava and Srivastava (1995) and Usha and Prema (1996) have studied the effects of Poiseulle flow on peristaltic transport of a particle fluid suspension with the small amplitude perturbation analysis. The Poiseuille flow interaction with peristalsis in an axisymmetric tube was investigated by El Shehawey and El. Sebacei (2001). Peristaltically driven channel flows with applications toward micro mixing have been studied by Selverov and Stone (2001).

Many of the theoretical investigations just mentioned have been carried out by assuming the blood and other physiological fluids to behave like a Newtonian fluid. Although this approach provides a satisfactory understanding of the peristaltic mechanism in the ureter, it fails to give a better understanding when the peristaltic mechanism is involved in small blood vessels, lymphatic vessels, intestine, ductus efferentes of the male reproductive tract and in transport of spermatozoa in the cervical canal. It has now been accepted that most of the physiological fluids behave like a non-Newtonian fluids. However only a few recent studies (Srivastava and Saxena, 1995; Bhome and Friedrich, 1983; Srivastava and Srivastava, 1988; Siddiqui and Schwarz, 1994) have considered this aspect of the problem since the initial investigation by Raju and Devanathan (1972, 1974). It has been pointed out that the flow behaviour of blood in vessels of small diameter (0.02cm) and at low shear rates (<20 s⁻¹) can be represented by a power law fluid (Charm and Kurland: 1965, 1974). In addition, physiological organs are generally observed to be a non-uniform duct (Wiedeman, 1963; Lee and Fung, 1971). Hence, peristaltic analysis of a Newtonian fluid with a uniform geometry cannot be applied when explaining the mechanism transport of fluid in most bio-systems. Srivastava et al. (1983) have studied peristaltic transport of Newtonian and non-Newtonian fluid in non-uniform geometries. The peristaltic flow of a third order fluid in a tube has been discussed by Siddiqui and Schwarz


The magnetohydrodynamic (MHD) flow of a fluid in a channel with elastic, rhythmically contracting walls (peristaltic flow) is of interest in connection with
certain problems of the movement of conductive physiological fluids, e.g., the blood and blood pump machines, and with the need for theoretical research on the operation of a peristaltic MHD compressor. The effect of moving magnetic field on blood flow was studied by Stud et al. (1977), and they observed that the effect of suitable moving magnetic field accelerates the speed of blood. Srivastava and Agrawal (1980) considered the blood as an electrically conducting fluid and constitute a suspension of red cell in plasma. Also, Agrawal and Anwaruddin (1984) studied the effect of magnetic field on blood flow by taking a simple mathematical model for blood through an equally branched channel with flexible walls executing peristaltic waves using long wavelength approximation method and observed, for the flow of blood in arteries with arterial disease like arterial stenosis or arteriosclerosis, that the influence of magnetic field may be utilized as a blood pump in carrying out cardiac operations. El-Shehawey and Husseny (2002) studied peristaltic transport of a magneto-fluid with porous boundaries. It has been noticed that the mean axial velocity and the reversal flow decrease by increasing the magnetic parameter. Abd El Hakeem et al. (2003) discussed peristaltic flow of an incompressible Newtonian fluid with variable viscosity subject to a constant transverse magnetic field. They notice that the increasing magnetic field increases pressure rise. Mekheimer (2004) studied peristaltic flow of blood under the influence of a magnetic field in non-uniform channels. Recently, Abd El Hakeem et al. (2006) investigated peristaltic transport of a non-Newtonian fluid through a uniform tube subject to a constant transverse magnetic field. Hayat et al. (2007) have investigated the peristaltic flow of a third order fluid under the effect of a magnetic field in a planar channel. Hayat et al. (2007) have studied the non-linear peristaltic flow of a fourth grade fluid in a planar channel under the effect of a magnetic field. Hayat et al. (2007) have discussed the peristaltic flow of a Jeffrey fluid under the effect of a magnetic field in a circular tube.
In recent years, flow through a porous medium has been of significant interest, particularly among geophysical fluid dynamicists. Examples of natural porous media are beach sand, sandstone, limestone, rye bread, wood, the human lung, bileduct, gall bladder with stones and in small blood vessels. The first study of peristaltic flow through a porous medium is presented by Elsehawey et al., (1999). The interaction of peristaltic flow with pulsatile fluid under the effect of a transverse magnetic field through a porous medium bounded by a two-dimensional channel is studied by Afifi and Gad (2001). Mekheimer and Arabi (2003) studied the non-linear peristaltic transport of MHD flow through a porous medium. Non-linear peristaltic transport through a porous medium in an inclined planar channel has studied by Mekheimer (2003) taking into account the gravity effect on pumping characteristics. Afifi and Gad (2003) have studied the interaction of peristaltic flow with pulsatile fluid through a porous medium. The peristaltic transport of a Maxwell fluid though a porous medium with hall effects was investigated by Hayat et al. (2007).