33

BIOMEDICAL ENGINEERING

33.1 INTRODUCTION

Biomedical Engineering (BME) is a relatively new discipline in the engineering profession and, as one might expect, it has come to mean different things to different people. Terms such as biomedical engineering, biochemical engineering, bioengineering, biotechnology, biological engineering, genetic engineering, and so on, have been used interchangeably by many in the technical community. To date, standard definitions have not been created to distinguish these genres. Consequently, we will lump them all using the term BME for the sake of simplicity. What one may conclude from all of the above is that BME involves applying the concepts, knowledge, basic fundamentals, and approaches of virtually all engineering disciplines (not only chemical engineering) to solve specific health and health-care related problems; the opportunities for interaction between engineers and health-care professionals are therefore many and varied.

On a personal note, the authors view BME as the application of engineering, mathematics, and physical sciences to principles in biology and medicine. The terms biophysics and bioengineering either involve the interaction of physics or engineering with either biology or medicine.

Because of the broad nature of this subject, this introductory chapter addresses only the application of BME to the anatomy of humans, particularly the cardiovascular system, and attempts to relate four key anatomy topics to fluid flow. The reader is referred to three excellent references in the literature for an extensive comprehensive treatment of this new discipline.[1-3]

Fluid Flow for the Practicing Chemical Engineer. By J. Patrick Abulencia and Louis Theodore

The four key cardiovascular "parts" to be discussed in subsequent sections are:

1. Blood.
2. Blood vessels.
3. Heart.
4. Plasma–cell flow.

The relation of these topics to the general subject of fluid flow is provided in Table 33.1.[4] Thus, from a fluid flow and engineering perspective, the cardiovascular system is comprised of a pump (heart) that generates a pressure difference driving force that involves the flow of a fluid (blood), where the fluid involves the transport of a two-phase medium (plasma and cells), through a complex network of pipes (blood vessels). As noted earlier, BME may therefore be viewed as an interdisciplinary branch of technology that is based on both engineering and the sciences.

Table 33.1 Fluid flow analogies

Topic	Fluid Flow	Biomedical Engineering
Fluid flow	Fluid	Blood
Conduit	Pipe	Blood vessels
Prime mover	Pump	Heart
Two-phase flow	Fluid-particle dynamics	Plasma-cell flow

Following a section on definitions, each of the aforementioned topics receives a qualitative treatment from a fluid flow perspective. The chapter concludes with an abbreviated description of job opportunities and activities in the biomedical engineering field while briefly alluding to regulatory issues.

33.2 DEFINITIONS

The definition of a host of BME and BME-related terms is provided below. A one-sentence (in most instances) description/explanation of each word/phase is provided. As one might suppose, the decision of what to include (as well as what to omit) was somewhat difficult.

1. Anatomy: The structure of an organism or body; its dissection to determine body parts.
2. Aorta: The key artery of the body that carries blood from the left ventricle of the heart to organs.
3. Artery: Any one of the thick-walled tubes that carry blood from the heart to the principal parts of the body.
4. Atrium: Either the left or right upper chamber of the heart.

5. Autonomic nervous system: The functional division of the nervous system that innervates most glands, the heart, and smooth muscle tissue in order to maintain the internal environment of the body.
6. Capillary: Any of the extremely small blood vessels connecting the arteries with veins.
7. Cardiac muscle: Involuntary muscle possessing much of the anatomic attributes of skeletal voluntary muscle and some of the physiologic attributes of involuntary smooth muscle tissue; sinoatrial node induced contraction of its interconnected network of fibers allows the heart to expel blood during systole.
8. Cell: An extremely small complex unit of protoplasm, usually with a nucleus, cytoplasm, and an enclosing membrane; the semielastic, selectively permeable cell membrane controls the transport of molecules into and out of a cell.
9. Chronotropic: Affecting the periodicity of a recurring action such as the slowing (bradycardia) or speeding up (tachycardia) of the heartbeat that results from extrinsic control of the sinoatrial node.
10. Circulatory system: The course taken by the blood through the arteries, capillaries, and veins and back to the heart.
11. Clot: A clot consists primarily of red corpuscles enmeshed in a network of fine fibrils or threads, composed of a substance called fibrin.
12. Corpuscle: An extremely small particle, especially any of the erythrocytes or leukocytes that are carried and/or float in the blood.
13. Cytoplasm: The protoplasm outside the nucleus of a cell.
14. Endocrine system: The system of ductless glands and organs secreting substances directly into the blood to produce a specific response from another "target" organ or body part.
15. Endothelium: Flat cells that line the innermost surfaces of blood and lymphatic vessels and the heart.
16. Erythrocytes: Red corpuscles.
17. Gland: Any organ or group of cells that separates certain elements from the blood and secretes them in a form for the body to use or discard.
18. Heart: The organ that receives blood from the veins and pumps it through the arteries by alternate dilation and contraction.
19. Homeostasis: A tendency to uniformity or stability in an organism by maintaining within narrow limits certain variables that are critical to life.
20. Inotropic: Affecting the contractility of muscular tissue such as the increase in cardiac power that results from extrinsic control of the myocardial musculature.
21. Leukocytes: White corpuscles.
22. Nucleoplasm: The protoplasm that composes the nucleus of a cell.

23. Plasma: The fluid part of blood, as distinguished from corpuscles; its principal component is water.
24. Precapillary sphincters: Rings of smooth muscle surrounding the entrance to capillaries where they branch off from upstream metarterioles. Contraction and realization of these sphincters close and open the access to downstream blood vessels, thus controlling the irrigation of different capillary networks.
25. Protoplasm: A semifluid viscous colloidal that is the living matter of humans and is differentiated into nucleoplasm and cytoplasm.
26. Pulse: The expansion and contraction of the arterial walls that can be felt in all the arteries near the surface of the skin.
27. Stem Cells: A generalized parent cell spawning descendants that become individually specialized.
28. Vein: Any blood vessel that carries blood from some part of the body back to the heart; in a loose sense any blood vessel.
29. Ventricle: Either of the two lower chambers of the heart that receive blood from the atria and pump it into the arteries.

Since the difference between biomedical engineering and biochemical engineering/biotechnology are somewhat overlapping, several additional definitions in the latter subject are listed below[5]:

1. Algae: Algae are a very diverse group of photosynthetic organisms that range from microscopic size to lengths that can exceed the height of a human.
2. Bacteria: The bacteria are tiny single-cell organisms ranging from 0.5–20 μm in size although some may be smaller, and a few exceed 100 μm in length.
3. Fungi: As a group, fungi are characterized by simple vegetative bodies from which reproductive structures are elaborated; all fungal cells possess distinct nuclei and produce spores in specialized fruiting bodies at some stage in their life cycle.
4. Microorganism: A class of organisms that includes bacteria, protozoan, viruses, and so on.
5. Photosynthesis: All living cells synthesize Adenosine 5′-triphosphate (ATP), but only green plants and a few photosynthetic (or phototrophic) microorganisms can drive biochemical reactions to form ATP with radiant energy though the process of photosynthesis.
6. Protozoan: A single cell or a group of essentially identical cells living primarily in water.
7. Viruses: Viruses are particles of a size below the resolution of the light microscope and are composed mainly of nucleic acid, either DNA or RNA, surrounded by a protein sheath.
8. Yeasts: Yeasts are a kind of fungi; they are unicellular organisms surrounded by a cell wall and possessing a distinct nucleus.

33.3 BLOOD

Blood. It has been justifiably described as the "river of life." It is the transport medium that serves as a dispenser and collector of nutrients, gases, and waste that allows life to be sustained.

In terms of composition, blood is primarily composed of water. The average human contains about 5 L (5000 mL) of blood. This 5 L volume of blood contains in numbers (approximately):

5×10^{16} red corpuscles (erythrocytes)
1×10^{14} white corpuscles (leukocytes)
2.5×10^{15} platelets (thrombocytes)

The red blood cells are typically round disks, concave on two sides, and approximately 7.5 μm in diameter. They are made in the bone marrow and have a relatively robust lifespan of 120 days. These cells take up oxygen as blood passes through the lungs, and subsequently release the oxygen in the capillaries of tissues. From a mechanics aspect, red blood cells have the ability to deform. This is important because erythrocytes often have to navigate through irregular shapes within the vasculature, as well as squeeze through small diameters such as those encountered in capillaries.

In contrast, white blood cells serve a wider variety of functions. These cells can be classified into two categories based on the type of granule within their cytoplasm, and the shape of the nucleus. More specifically, the two categories are: 1) Granulocytes or Polymorphonuclear (PMN) leukocytes, and 2) Mononuclear leukocytes. Examples of PMNs include neutrophils, eosinophils, and basophils, while those of mononuclear leukocytes include lymphocytes and monocytes.

Platelets are small, round, non-nucleated disks with a diameter about one-third that of red blood cells. They are formed from megakaryocytes in the bone marrow, and have a 7 to 10 day lifespan within the vasculature. The main function of platelets is to arrest bleeding.

The final component of blood is plasma, and is the fluid in which the aforementioned cells remain in suspension. It is comprised primarily of water (90%), and the rest plasma protein (7%), inorganic salts (1%), and organic molecules such as amino acids, hormones, and lipoproteins (2%). The primary functions of plasma are to allow exchange of chemical messages between distant parts of the body, and maintenance of body temperature and osmotic balance.[6]

In terms of physical properties, the density of blood (as one might suppose) is approximately that of water, that is, 1.0 g/cm^3 or 62.4 lb/ft^3. The other key property is viscosity and it is approximately 50% greater than that for water. The reader is no doubt familiar with the expression "blood is thicker than water." Well, it turns out not to be that much "thicker" than water since its viscosity is only moderately higher. In addition, the viscosity is a strong function of temperature; it has been reported that the viscosity increases by 50% over the 20–40°C range. Although plasma (the main constituent of blood) is Newtonian, blood (with the added blood cells) is non-Newtonian.

Illustrative Example 33.1 The viscosity of plasma has been estimated to be 1.25 cP at room temperature. Convert this to English units.

Solution Convert viscosity from centipoises to lb/ft · s.

$$(1.25\,\text{cP})\left(\frac{6.72 \times 10^{-4}\,\text{lb}}{\text{ft} \cdot \text{s} \cdot \text{cP}}\right) = 8.4 \times 10^{-4}\,\text{lb/ft} \cdot \text{s}$$

$$= 0.00084\,\text{lb/ft} \cdot \text{s}$$

33.4 BLOOD VESSELS

The study of the motion of blood is defined as hemodynamics. Part of the cardiovascular system involves the flow of blood through a complex network of blood vessels. Blood flows through organs and tissues either to nourish and sanitize them or to be itself processed in some sense, e.g., to be oxygenated (pulmonary circulation), filtered of dilapidated red blood cells (splenic circulation), and so on.[3] The aforementioned "river of life" flows through the piping network, which is made up of blood vessels, by the action of two pump stations arranged in series. This complex network also consists of thousands of miles of blood vessels. The network also consists of various complex branching configurations.

Regarding the branching, the aorta divides the discharge from the heart into a number of main branches, which in turn divide into smaller ones until the entire body is supplied by an elaborately branching series of blood vessels. The smallest arteries divide into a fine network of still more minute vessels, defined as capillaries, which have extremely thin walls; thus, the blood is enabled to come into close relation with the fluids and tissues of the body.

In the capillaries, the blood performs three functions:

1. It releases oxygen to the tissues.
2. It furnishes the nutrients and other essential substances that it carries to the body cells.
3. It takes up waste products from the tissues.

The capillaries then unite to form small veins. The veins, in turn, unite with each other to form larger veins until the blood is finally collected into the venal cavae from where it goes to the heart, thus completing the blood vessel circuit (see next section for additional details). This complex network is designed to bring blood to within a capillary size of each and every one of more than 10^{14} cells of the body. Which cells receive blood at any given time, how much blood they get, the composition of the fluid flowing by them, and related physiologic considerations are all matters that are not left up to chance.[1]

Information on average radius and number of each of the various vessels has been provided by LaBarbara.[7] His data/information is given in Table 33.2. The average diameter of blood vessels in humans has not been determined since there is a wide

Table 33.2 The average radii and total numbers of conventional categories of vessels of the human circulatory system

Vessel	Average Radius (mm)	Number
Aorta	12.5	1
Arteries	2	159
Arterioles	0.03	1.4×10^7
Capillaries	0.006	3.9×10^9
Venules	0.02	3.2×10^8
Veins	2.5	200
Vena cava	15	1

distribution of sizes, but based on the data in Table 33.2, one may assume the value of 150 μm for the smaller vessels.

Illustrative Example 33.2 The usual units employed for pressure in cardiovascular studies is mmHg. Convert 80 mm Hg to in Hg, ft H_2O, in H_2O, psia, psfa, and N/m^2.

Solution Expressed in various units, the standard atmosphere is equal to:

1.0	Atmospheres (atm)
33.91	Feet of water (ft H_2O)
14.7	Pounds-force per square inch absolute (psia)
2116	Pounds-force per square foot absolute (psfa)
29.92	Inches of mercury (in Hg)
760	Millimeters of mercury (mm Hg)
1.013×10^5	Newtons per square meter (N/m^2)

Applying the conversion factors to 80 mm Hg from above leads to:

$$
\begin{aligned}
P &= 80(29.92/760) \\
&= 3.15 \text{ in Hg} \\
P &= 80(33.91/760) \\
&= 3.57 \text{ ft } H_2O \\
P &= (3.57)(12) \\
&= 42.8 \text{ in. } H_2O \\
P &= 80(14.7/760) \\
&= 1.55 \text{ psia} \\
P &= 80(2116/760) \\
&= 223 \text{ psfa} \\
P &= 80(1.013 \times 10^5/760) \\
&= 1.07 \times 10^4 \text{ N/m}^2
\end{aligned}
$$

Illustrative Example 33.3 Describe the role arteries play on a heart attack.

Solution Coronary arteries are very small in diameter and can become narrow as fatty deposits (plaque) build up. As the vessels narrow, less blood can get through to the heart when it needs it. If the heart is not getting enough oxygen to meet its needs, one may experience pain (angina). When the heart muscle does not receive enough oxygen-rich blood, it can become injured since oxygen is important to help keep the heart functioning properly. If blood flow is completely cut off for more than a few minutes, muscle cells die, causing a heart attack.

Illustrative Example 33.4 Discuss why the flow of blood through blood vessels can be safely assumed to be laminar flow.

Solution For flow in circular conduits, the flow is laminar if the Reynolds number

$$\mathrm{Re} = Dv\rho/\mu$$

is less than 2100. In nearly all biomedical applications, the numerical values for D and v are extremely small while the viscosity is large.

From an engineering perspective, one should note that vessel flow is laminar and the equations presented in Chapter 13 may be assumed to apply. For example, the velocity profile of the blood in the vessel may be assumed to be parabolic with the average velocity equal to one-half the maximum velocity. Equation 13.7 applies so that

$$\Delta P = \frac{4fLv^2}{2g_cD} \tag{33.1}$$

For laminar flow, see Equation (13.6)

$$f = 16/\mathrm{Re} \tag{33.2}$$

so that

$$\Delta P = \frac{32\mu gvL}{g_cD^2} \tag{33.3}$$

This equation may also be expressed in terms of the volumetric flow rate (setting $g/g_c = 1.0$)

$$\Delta P = \frac{128q\mu L}{\pi D^4} \tag{33.4}$$

Equation (33.4) may also be written:

$$q = \frac{\pi D^4(\Delta P)}{128\mu L} \tag{33.5}$$

Since the flow is laminar, the relative irregularity of the inner wall of the blood vessel has a negligible effect (see Chapter 14) on the volumetric flow-pressure drop relationship.

The blood vessel branching discussed above may be viewed as flow through a number of pipes or conduits, an application that often arises in engineering practice. If flow originates from the same source and exits at the same location, the pressure drop across each conduit must be the same. Thus, for flow through conduits 1, 2, and 3, one may write:

$$\Delta P_1 = \Delta P_2 = \Delta P_3 \tag{33.6}$$

From a fluid flow perspective, the presence of blood vessel branching enhances the performance of the cardiovascular circulatory system. When branching involves flow into smaller diameter vessels, the oxygen has a shorter distance and shorter residence time requirement to reach the tissues that require oxygen. In addition, if the velocity through the branched vessels remains unchanged, the pressure drop correspondingly decreases. This drop is linearly related to the diameter though equation (33.3).

Illustrative Example 33.5 If an artery branches into two smaller equal area arteries so that the velocity through the three arteries is the same, determine the ratio of the inlet and discharge artery diameters.

Solution Based on the problem statement and continuity

$$q = q_1 + q_2$$

Since

$$v = q/S$$

and

$$q_1 = q_2 = q/2$$

Therefore

$$S_1 = S_2 = S/2$$

and

$$\frac{\pi D_1^2}{4} = \frac{\pi D^2}{4(2)}$$

$$\left(\frac{D}{D_1}\right)^2 = 2$$

$$\frac{D}{D_1} = 2^{0.5} = 1.414$$

Alternately

$$\frac{D_1}{D} = 0.707$$

Illustrative Example 33.6 A blood vessel branches into three openings. Information on the system is provided in Table 33.3. Determine the magnitude velocity v_3.

Table 33.3 Flow velocity-area data for Illustrative Example 33.6

Vessel	Flow Area (m^2)	Velocity (mm/s)
Inlet	0.2	5
1	0.08	7
2	0.025	12
3	0.031	?

Solution Calculate the volumetric flow rate through the inlet Sections 1 and 2:

$$q = (0.2)(5) = 1\,(\text{mm})^3/\text{s}$$

$$q_1 = (0.08)(7) = 0.56\,(\text{mm})^3/\text{s}$$

$$q_2 = (0.025)(12) = 0.3\,(\text{mm})^3/\text{s}$$

Since the blood may be assumed to be of constant density, the continuity equation may be applied on a volume rate basis:

$$q = q_1 + q_2 + q_3$$

$$q_3 = q - q_1 - q_2$$

$$= 1 - 0.56 - 0.3$$

$$= 0.14\,(\text{mm})^3/\text{s}$$

The velocity v_3 is therefore:

$$v_3 = \frac{0.14}{0.031}$$

$$= 4.52\,\text{mm/s}$$

The equations developed for laminar flow between two or more parallel plates may also be assumed to apply. The flow is still parabolic but the maximum velocity is only 50% greater than the average value. For the interested reader, there are several biological applications that involve closely spaced and parallel plates.[4]

Finally, it should be noted that the:

1. Flow is pulsating.
2. Fluid is non-Newtonian.

3. Blood vessels vary in cross-sectional area.
4. Blood vessels vary in shape.
5. Terms (3) and (4) vary with time.

Despite the above five limitations, efforts abound that have attempted to model the flow of the "river of life" in the cardiovascular complex blood vessel network.

33.5 HEART

The "river of life" flows through the cardiovascular circulatory system by the action of the heart, which essentially provides two pumps that are arranged in series. (See Chapter 17, Section on flow in pumps arranged in series.)

In simple terms, the heart is an organ that receives blood from veins and propels it into and through the arteries. It is primarily held in place by its attachment to the aforementioned arteries and veins, and by its confinement, via a double-walled sac with one layer enveloping the heart and the other attached to the breastbone. Furthermore, the heart consists of two parallel independent systems, each consisting of an atrium and a ventricle that have been referred to as the right heart and the left heart.

The following is a description of the cardiovascular circulatory system. The heart is divided into four chambers through which blood flows. These chambers are separated by valves that help keep the blood moving in the right direction. The chambers on the right side of the heart take blood from the body and push it through the lungs to pick up oxygen. The left side takes blood from the lungs and pumps it out the aorta. The blood squeezes through a system of arteries, capillaries, and veins that reach every part of the body. The cycle is completed when the blood is returned to the heart by the superior and inferior vena cava and enters the atrium (or chambers) on the upper right side of the heart.

Regarding details of the action of the heart, blood is drawn into the right ventricle by a partial vacuum when the lower chamber relaxes after a beat. On the next contraction of the heart muscle, the blood is squeezed into the pulmonary arteries that carry it to the left and right lungs. The blood receives a fresh supply of oxygen in the lungs and is pumped into the heart by way of the pulmonary veins, entering at the left atrium. The blood is first drawn into the left ventricle and then pumped out again through the aorta (the major artery), which connects with smaller arteries and capillaries reaching all parts of the body. Thus, the cardiovascular circulatory system consists of the heart (a pump), the arteries (pipes) that transport blood from the heart, and the capillaries and veins (pipes) that transport the blood back to the heart. These form a complete recycle process. An expanded discussion of the process is provided in the next paragraph.

A line diagram of the recycle circulatory system is given in Fig. 33.1.[5] The cycle begins at point 1. Oxygenated blood is pumped from the left lower ventricle (LLV) at an elevated pressure through the aorta and discharge oxygen to various parts of the body. Deoxygenated blood then enters the right upper atrium (RUA), passes

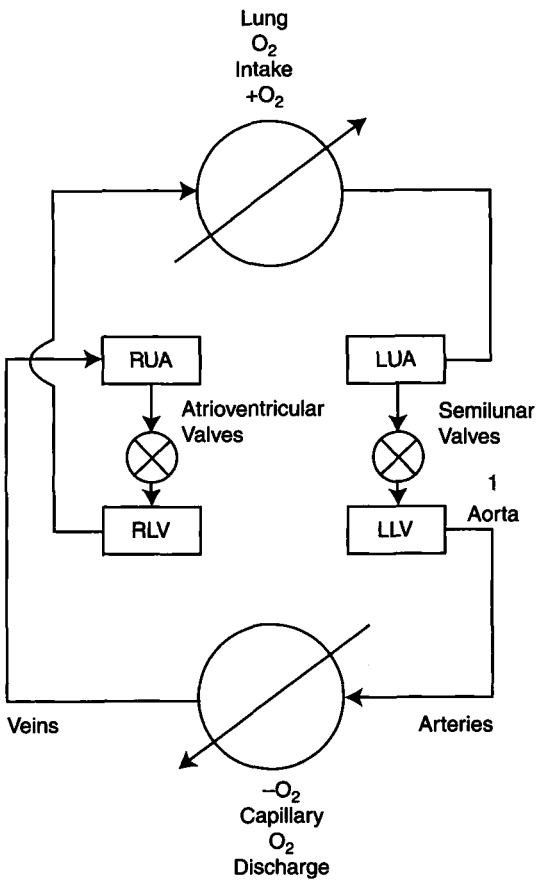

Figure 33.1 Cardiovascular circulatory system.

through the right lower ventricle (RLV) and then enters the lungs where its oxygen supply is replenished. The oxygenated discharge from the lungs enters the left upper atrium (LUA) and returns to the lower left ventricle, completing the cycle.

As noted above, the concepts regarding recycle, bypass and purge presented in Chapter 7 readily apply to the discussion above. In addition to blood being recycled through the circulatory system, it is also being reused. Bypass occurs when part of the blood is bypassed to the liver for cleansing purposes. The purging process may be viewed as occurring during the oxygen transfer to tissues as well as the aforementioned cleansing process.

The typical discharge with each heart beat is 70 mL through the 2.4 cm diameter pulmonary vessel and the 2.25 cm diameter aortic vessel. The return of the 70 mL (from the continuity equation) of blood to the heart enters from the 3.8 cm diameter right atrium and the 3.1 cm diameter left atrium. This discharge occurs approximately

every 0.75 s, or the equivalent of 80 heartbeats/min. This translates to a volumetric flow rate of

$$\begin{aligned} q &= 70/0.75 \\ &= 93.3\,\text{mL/s} \end{aligned}$$

This corresponds to a circulation rate of slightly more than 5 L/min.

Illustrative Example 33.7 Calculate the average velocity of blood flowing through the aorta. Assume the diameter of the aorta is 2.5 cm.

Solution The area for flow in the aorta is

$$\begin{aligned} S &= (\pi/4)(2.5)^2 \\ &= 4.9\ \text{cm}^2 \end{aligned}$$

Since the volumetric flow rate is 93.3 mL/s (93.3 cm^3/s), the velocity is

$$\begin{aligned} v &= q/S \\ &= 93.3/4.9 \\ &= 19\,\text{cm/s} \end{aligned}$$

Illustrative Example 33.8 One of the authors of this book is 74 years old (at the time of the preparation of this manuscript). Based on the data provided above, calculate the number of times (T) that the author's heart has beat to date.

Solution

$$\begin{aligned} T &= [(74)(365)(24)(60)](80) \\ &= 3{,}110{,}000{,}000 \\ &= 3.11 \times 10^9 \end{aligned}$$

Thus, the author's heart has already beaten approximately 3 billion times over his 74 year lifespan.

Illustrative Example 33.9 Refer to Example 33.8. Calculate the volume of blood that has circulated through the author's system over his lifetime.

Solution Again, being careful to be dimensionally consistent, the volume of blood (V) is

$$\begin{aligned} V &= (3.11 \times 10^9)(70) \\ &= 2.18 \times 10^{11}\,\text{mL} \\ &= 2.18 \times 10^8\,\text{L} \end{aligned}$$

This represents approximately 200 million liters of blood.

To summarize, from a fluid flow/engineering perspective, the systemic circulation carries blood to the neighborhood of each cell in the body and then returns it to the right side of the heart low in oxygen and rich in carbon dioxide. The pulmonary circulation carries the blood to the lungs where its oxygen supply is replenished and its carbon dioxide content is purged before it returns to the left side of the heart to repeat the cycle. The driving force for flow arises from the pressure difference between the high pressure left side of the heart (systemic) to the lower pressure right side (pulmonary). This pressure difference provides the impetus for the "river of life" to flow. Thus, the heart may be viewed as an engine pump that has many of the characteristics of a centrifugal pump.

Regarding physical properties of the heart, it is approximately the size of a clenched fist. It is inverted, conically-shaped, measuring 12 to 13 cm from base (top) to apex (bottom) and 7 to 8 cm at its widest point and weighing just under 0.75 lb (less than 0.5% of a human's body weight) and located between the third and sixth ribs. It rests between the lower part of the two lungs.[3]

Illustrative Example 33.10 Dr. Abs, one of the foremost authorities in the biomedical field has concluded, based on many years of a theoretical modeling study that the flow of blood from the aorta to the atrium could be physically represented by a 0.3-mile long 2.5 cm diameter vessel. Is the model a reasonable one if the blood velocity is 19 cm/s (see Illustrative Example 33.7)?

Solution At a minimum, the pressure drop (ΔP) calculation across the heart should approximately be

$$\begin{aligned}\Delta P &= 120 - 80 \\ &= 40\,\text{mmHg}\end{aligned}$$

Apply Equation (33.3) and assume that the density and viscosity of the blood are 62.4 lb/ft^3 and 1.1 cP, respectively

$$\Delta P = \frac{32\mu g v L}{\rho g_c D^2} \tag{33.3}$$

Substituting,

$$\begin{aligned}\Delta P &= \frac{32(1.1)(6.72 \times 10^{-4})(19/30.48)(5280)(0.3)}{(62.4)(2.53/30.48)^2(32.2)} \\ &= 1.729\,(\text{ft})(\text{lb}_\text{f})/\text{lb} \\ &= 107.8\,\text{lb}_\text{f}/\text{ft}^2 \\ &= 38.7\,\text{mmHg}\end{aligned}$$

The model is reasonable from a fluid dynamics perspective.

Illustrative Example 33.11 A new blood vessel has been implanted in a patient's circulatory system. Which of the following three options, with dimensions specified, would provide the least resistance to flow of a given quantity of blood?

1. $D = 2.5$ cm, $L = 5$ cm
2. $D = 1.25$ cm, $L = 2.5$ cm
3. $D = 5.0$ cm, $L = 10$ cm

Solution Assuming laminar flow, apply Equation (33.1). Assign (1) as the base case value

$$\Delta P_1 = \frac{32\mu g v L}{\rho g_c D^2}$$
$$= (K)(Lv/D^2);\ K = 32\,\mu g/eg_c$$

For (2),

$$\Delta P_2 = K(0.5L)(4v)/(0.5D^2)$$
$$= K(8)(Lv/D^2) = 8(K)(Lv/D^2)$$

For (3),

$$\Delta P_3 = K(2\,L)(0.25v)/(2D^2)$$
$$= K(0.125)(Lv/D^2) = 0.125(K)(Lv/D^2)$$

As expected, (3) provides the lowest pressure drop while (2) provides the highest resistance.

With reference to Fig. 17.2 in Chapter 17, note the relationship between the volume rate of flow and the pressure difference generated by the pump. The pump can operate anywhere within the circular curve, which is referred to as the pump curve. The line from the origin represents the system curve and intersects the pump curve at the maximum output of the pump for those conditions. Notice that for low-pressure drop conditions, the maximum flow rate is not overly sensitive to the pressure drop with which the pump must contend. As can be seen from Fig. 17.2, the pressure increase developed by a pump is a function of the discharge rate. As with a real pump, when the flow rate increases, the pressure increase delivered by the pump decreases. In fact, the pump's power is given by the product of the two terms, that is, the pressure drop and volumetric flow rate

$$\text{hp} = q\Delta P \tag{33.7}$$

For the heart, hp represents the power required to maintain the recycle process that constitutes the circulatory flow of the blood in the cardiovascular system.

Illustrative Example 33.12 Estimate the power generated by the human heart. Assume the pressure drop in the circulatory system is 60 mm Hg.

Solution

$$\text{hp} = q\Delta P \tag{33.7}$$

As noted earlier, $q = 93.3$ mL/s.

Converting,

$$q = 0.0033\,\text{ft}^3/\text{s}$$

Substitution gives

$$\text{hp} = (0.0033)(60)(14.7) * (144)/760$$
$$= 10 \times 10^{-4}\ \text{hp}$$

33.6 PLASMA/CELL FLOW

As described earlier, blood is comprised of a fluid called plasma and suspended cells that primarily include erythrocytes (red blood cells), leukocytes (white blood cells), and platelets. From a fluid dynamics perspective, blood motion can be viewed as a fluid–particle application involving a two-phase flow. As noted in both Chapters 16 and 23, a rigorous theoretical description of flow with a concentrated suspension of particles is not available. Unfortunately, such a description is necessary for a quantitatively accurate understanding of the flow of blood in blood vessels.

The blood vessels through which the blood flows has dimensions that are small enough so that the effects of the particulate nature of blood should not be ignored. As noted earlier, blood consists of a suspension of red blood cells, white blood cells, and platelets in plasma. Strictly speaking, the describing equations and calculation presented earlier for both flow and pressure drop are valid only under restricted conditions. The equations are not strictly valid if[8]:

1. The particle is not "very" small.
2. The particle is not a smooth rigid sphere.
3. The particle is located "near" the surrounding walls containing the fluid.
4. The particle is located "near" one or more other particles.
5. The motion of the fluid and particle is multidimensional.
6. Brownian motion effect is significant.

Each of the above topics is treated briefly below.[8] Despite the above limitations, it should be noted that these effects are rarely included in any traditional engineering analysis of a fluid-particle system. It is more common to use an empirical constant or factor that would account for all of these various effects.

1. At very low values of the Reynolds number, when particles approach sizes comparable to the mean free path of the fluid molecules, the medium can no longer be regarded as continuous since particles can move between the molecules at a faster rate than predicted by the aerodynamic theories, which leads to standard drag coefficients. To allow for this "slip," Cunningham introduced a multiplying correction factor to Stokes' law; details are available in Chapter 23.
2. For particles having shapes other than spherical, it is necessary to specify the size and geometric form of the body and its orientation with respect to the direction of flow of the blood. One major dimension is chosen as the characteristic length and other important dimensions are given as ratios to the chosen one. Such rations are called shape factors. Nonspherical bodies generally tend to orient in a preferred direction during motion; actually, orientation is another effect that needs to be considered. For example, at high Reynolds numbers, a disk always settles horizontally with its flat face perpendicular to its motion; a streamlined shape, on the other hand, falls nose down into its position of least resistance. At low Reynolds numbers, a particle such as a disk or ellipsoid with three perpendicular symmetry planes can settle in any position.
3. In most engineering applications, the particles are negligibly small when compared to the dimensions of the conduit; therefore, wall effects can usually be neglected. However, in blood flow wall effects can be more pronounced. Theoretical considerations or experimental work has established factors for modifying the describing equation to account for wall effects under different sets of circumstances.
4. In most biomedical applications, it is almost inevitable that large numbers of particles will be involved. It is also very likely that the particles will influence one another. Therefore, equations for the fluid resistance to the motion of single particles have to be modified to account for such interactions between particles. Particle interactions can become appreciable even at very low concentrations. Even a particle-volume concentration (the ratio of particle volume to total volume) of 0.2% will increase the fluid resistance to particle motion by about 1%. In general, for volume concentrations below 1%, the effect of particle interactions may be neglected.
5. Previous discussions on particle motion were limited to the unidimensional case, that is, the parallel movement of a particle relative to the fluid. However, this is often not the general case. This situation is defined as multidimensional flow. Equations must then be developed to describe each of the velocity components of the particle. The main complication arises if more than one relative velocity component exists.
6. As a result of bombardment by the molecules of the fluid medium, suspended particles will be subjected to a random motion known as Brownian movement. This effect becomes significant only when the particles are very small and their mass approaches that of the fluid molecules. Einstein[9] showed that Brownian movement, in general, becomes significant only for particles less than about 0.05 μm.

Illustrative Example 33.13 A 10-year biomedical research study generated data for the average number of heart attacks per 100 individuals in the same age group (H) and gender as a function of the number of quarts of beer that have been consumed per month (q). See Table 33.4.

Table 33.4 Data for Illustrative Example 33.13

H	q
3	10
3.6	30
4.44	100
5.19	250

Using the data in Table 33.4, estimate the coefficients a and b in the heart attack equation below:

$$H = a(q)^b$$

Solution Linearize the equation

$$\ln(H) = \ln(a) + (b)\ln(q)$$

Change variables to Y and X.

Set $\ln(H)$ equal to Y and $\ln(q)$ equal to X

$$Y = A + BX$$

where

$$A = \ln(a)$$
$$B = b$$

Regress the above data (4 data points) using the method of least squares. The method of least squares requires that the sum of the errors squared between the data and model is minimized

$$\ln(3) = A + B\ln(10)$$
$$\ln(3.6) = A + B\ln(30)$$
$$\ln(4.44) = A + B\ln(100)$$
$$\ln(5.19) = A + B\ln(250)$$

Generate the linear equation coefficients A and B. These may be obtained through a longhand calculation. However, they are more often obtained with the aid of computer software:

$$A = 0.704$$
$$B = 0.171$$

Obtain constants a and b by taking the inverse natural logarithm of A to obtain a

$a = 2.02$
$b = 0.171$

The heart attack equation is therefore

$$H = 2.02q^{0.171}$$

Information on data regression using the method of least squares is available in the literature.[10]

The reader should note that if more heart attack–quarts of beer data becomes available, thus increasing the number of points, then the calculated line may not be the best representation of all the data; the least squares solution should then be recomputed using all the data. In addition, the assumed model, for example, linear, may not be the "best" model.

33.7 BIOMEDICAL ENGINEERING OPPORTUNITIES

Key activities in this profession include[2,3]:

1. Development of improved species of plants and animals for food production.
2. Invention of new medical diagnostic tests for diseases.
3. Production of synthetic vaccines from clone cells.
4. Bioenvironmental engineering to protect human, animal, and plant life from toxicants and pollutants.
5. Study of protein-surface interactions.
6. Modeling of flow dynamics.
7. Modeling of mass transfer through membranes.
8. Modeling of the growth of kinetics of yeast and hybridoma cells.
9. Research in immobilized enzyme technology.
10. Development of therapeutic proteins and monoclonal antibodies.
11. Development of artificial hearts.

New applications that have emerged over the last half-century include[2,3]:

1. Application of engineering system analysis (physiologic modeling, simulation, and control of biological problems).
2. Detection, measurement, and monitoring of the physiologic signals (i.e., biosensors and biomedical instrumentation).
3. Diagnostic interpretation via signal-processing techniques of bioelectric data.

4. Therapeutic and rehabilitation procedures and devices (rehabilitation engineering).
5. Devices for replacement or augmentation of bodily functions (artificial organs).
6. Computer analysis of patient-related data and clinical decision-making (i.e., medical informatics and artificial intelligence).
7. Medical imaging, i.e., the graphical display of anatomic detail or physiologic functions.
8. The creation of new biologic products (i.e., biotechnology and tissue engineering).

Job-related activities of biomedical engineers include[2,3]:

1. Research into new materials for implanted artificial organs.
2. Development of new diagnostic instruments for blood analysis.
3. Writing software for analysis of medical research data.
4. Analysis of medical device hazards for safety and efficacy.
5. Development of new diagnostic imaging systems.
6. Design of telemetry systems for patient monitoring.
7. Design of biomedical sensors.
8. Development of expert systems for diagnosis and treatment of diseases.
9. Design of closed-loop control systems for drug administration.
10. Modeling of the physiologic systems of the human body.
11. Design of instrumentation for sports medicine.
12. Development of new dental materials.
13. Design of communication aids for individuals with disabilities.
14. Study of pulmonary fluid dynamics.
15. Study of biomechanics of the human body.
16. Development of material to be used as replacement for human skin.
17. Applications of nanotechnology to many of the above activates.

Obviously, these three lists are not intended to be all-inclusive. Many other applications are evolving that use the talents and skills of the biomedical engineer. This is a field where there is continual change and creation of new areas due to the rapid advancement in technology.

In terms of job opportunities, biomedical engineers are employed in universities, in industry, in hospitals, in research facilities of educational and medical institutions, in teaching, and in government and regulatory agencies. They can often serve a coordinating or interfacing function, using their background in both the engineering and medical fields to combine sound knowledge of engineering and the sciences.

Regulatory issues are a constant cause for concern and, perhaps, justifiably so. To satisfy safety regulations, most biomedical systems must have documented analysis of

risk to show that they were designed, built, tested, delivered, managed, and used according to a planned and approved process. The two key regulatory agencies in the US are the Food and Drug Administration (FDA) and the Consumer Product Safety Commission.

In conclusion, biomedical engineering is now an important vital interdisciplinary field. The ultimate role of the biomedical engineer and the profession is to serve society. The great potential, challenge, and promise in this relatively new endeavor offers both technological and humanitarian benefits. The possibilities appear to be unlimited.

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