CHAPTER 4
Basic Physiological Principles

Now that we have a working anatomical knowledge of the heart and circulatory system, we will next develop a functional and quantitative knowledge of the cardiovascular system.

4.1 Specific learning objectives for this chapter

A. Distribution of blood volumes within the cardiovascular system.
B. Arterioles and their function in controlling blood flow (resistance)
C. Capillaries and their function in material transfer
D. Venules
E. Venous valves and their function
F. Distribution of blood volumes in the circulatory system
G. Distributions of cross-sectional areas in the circulatory system
H. Ohm's law
I. Units of resistance in the CV system
J. Total peripheral resistance, total pulmonary resistance
K. Poiselle's law and its underlying assumptions
L. Volume-pressure curves of arteries and veins
M. Vascular compliance and it's units
N. Delayed compliance (stress-relaxation)
O. Venous reservoir function
P. Importance of right atrial pressure
Q. Venous resistance and compliance
R. Pressures in the circulatory system
S. Hydrostatic pressure
T. Mean circulatory filling pressure
U. Non-linear pressure / flow relationship

4.2 qualitative facts about the cardiovascular system

A general qualitative "feel" for the cardiovascular system can assist the cardiovascular engineer in modeling the system and developing assist devices. To this end, the following "qualitative facts" are presented.

General sectional properties of the systemic circulation can be seen in Figure 4.1. The average diameter of the blood vessel diminishes rapidly as one moves from the aorta down to the capillary level, at which point the average diameter begins to increase as one travels closer to the inferior/superior vena cava. The average blood pressure also falls rapidly, especially through the arteriolar level. The pressure drop in the venous system is much smaller than in the arterial system.

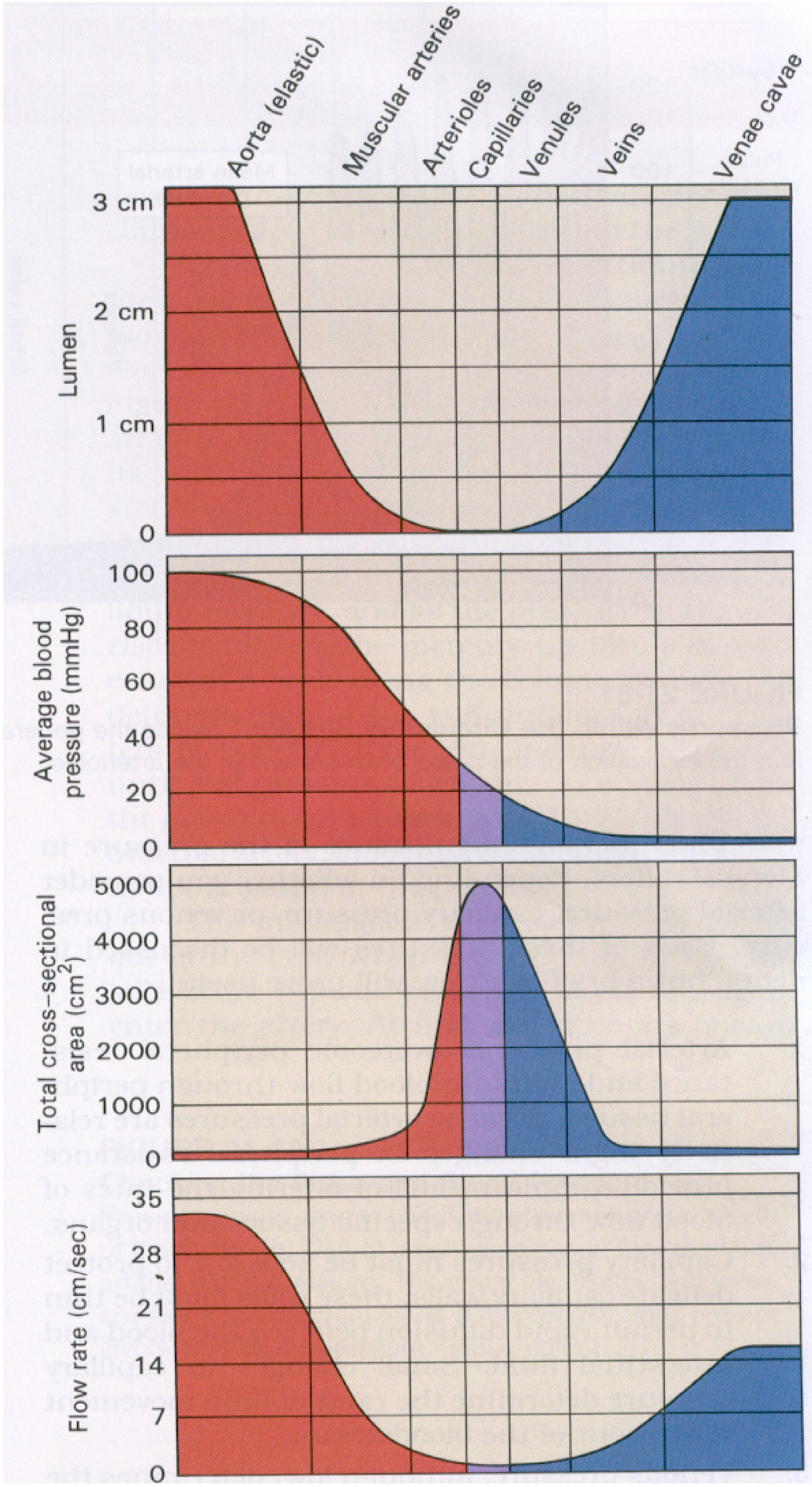

Figure 4.1 Cross-sectional properties of the Circulatory system

The total cross-sectional area of all the vessels as one travels down the arterial and venous systems is shown in the third panel of Figure 4.1. The maximum area is found in the capillaries, due to the great number of capillary vessels. As a result, the flow rate/vessel is minimum in the capillaries, which allows more time to transfer fuel and waste products.

Table 4.1 shows that the majority of the blood volume resides in the venous system, under normal conditions. The heart contains less than 10% of the total blood volume as does the pulmonary system.

Blood Volume Distributions,%	
Heart	7
Aorta	13
Arterioles/Capillaries	7
Pulmonary	9
Veins	64

Table 4.1

Figure 4.2 depicts what happens to the pulsatility and the average of the blood pressure waveform as the blood traverses the circulatory system. Obviously, the pulsatility is large until the arteriolar level is reached. Here the average drops from about 100 mmHg to about 30 mmHg. The pressure stays low until the right heart is reached, where nominally the right heart raises the pressure from about 0 mmHg to about 20 mmHg in the pulmonary arteries. The large pressure increases in the left heart (120 mmHg) are evident.

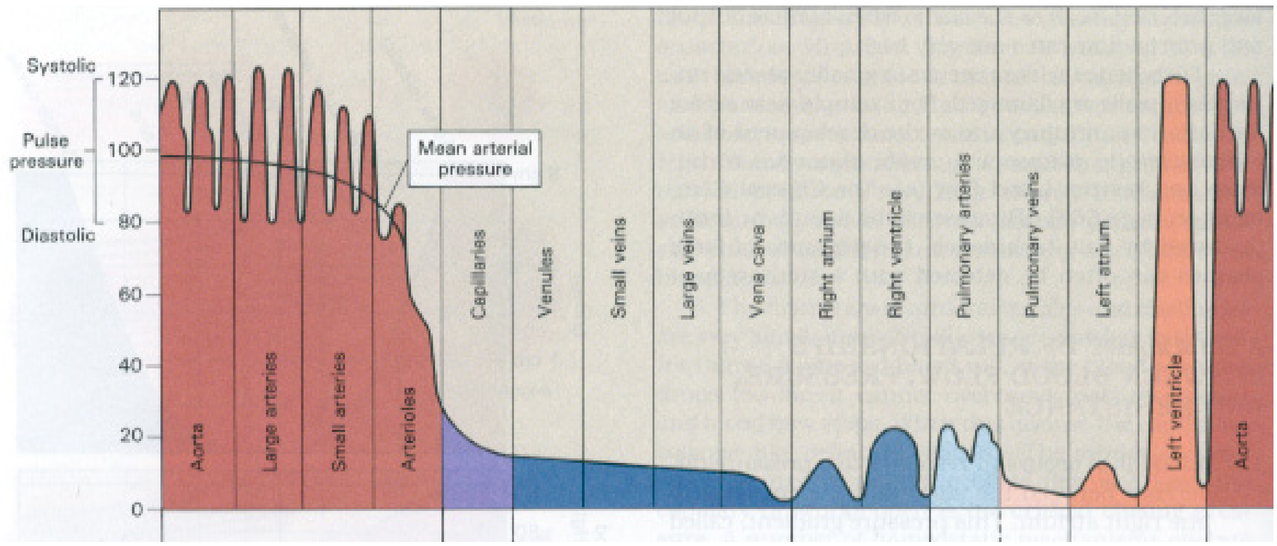

Figure 4.2 Pulsatility and Average Pressures Within the Cardiovascular System

Another issue to understand is that of hydrostatic pressure within the circulatory system. Hydrostatic pressure is due to gravity acting upon a column of fluid, in this case blood. The taller the column, the greater the pressure at the bottom of the column. Hydrostatic pressure is mathematically defined as

$$P_H = \rho g h$$

where, P_H = hydrostatic pressure
p = density of blood
g = gravitational constant
h = height of fluid column

Figure 4.3 shows the result of hydrostatic pressure on the blood pressure measured in various regions. Note especially that the venous blood pressure in the head can fall below atmospheric pressure (-10 mmHg). In the feet the pressure can reach close to 100 mmHg in the venous system.

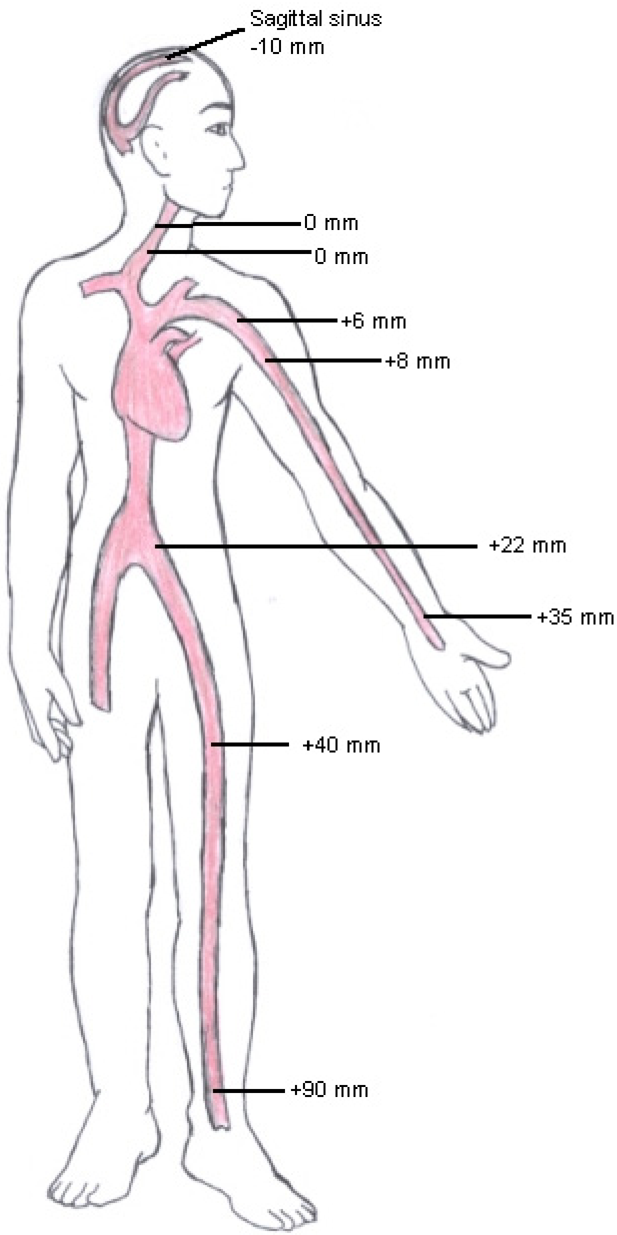

Figure 4.3 Hydrostatic Pressures

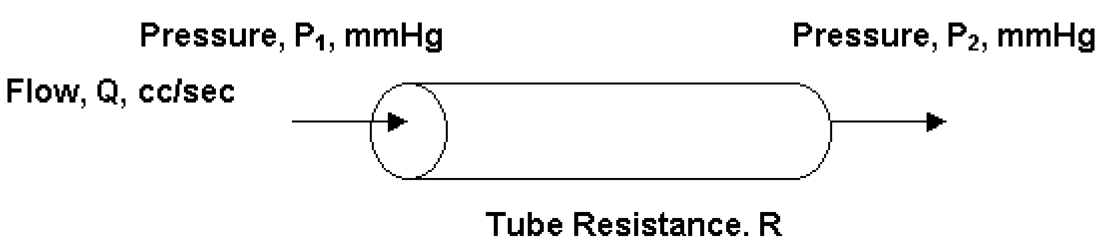

Figure 4.4 Relationship between Pressure drop and Flow

Next, we can study the movement of blood through a blood vessel. Let's assume that the blood is flowing in a steady manner. One can relate the pressure drop across a section of blood vessel to the flow rate by a resistance (Ohm's law).

$$R = \frac{(P_1 - P_2)}{Q}$$

The variable R has units of $\frac{\text{mmHg} \bullet \text{sec}}{\text{cc}}$ and this is called peripheral resistance units (PRU). Pouiselle discovered an important relationship between pressure and flow in long, thin, rigid tubes with steady flow. He found that for a tube as shown above, with length, L:

$$Q = \frac{n\pi r^4 (P_1 - P_2)}{8\eta L}$$

where,

n = number of tubes in parallel
π = pi
r = tube radius
η = fluid viscosity

Rearranging, one can find the resistance for this case to be:

$$R = \frac{8\eta L}{n\pi r^4}$$

Thus, resistance to fluid flow is highly dependent on the radius to the fourth power, and the higher the viscosity and length, the greater the resistance. The greater the number of tubes and the radius, the lower the resistance. As r gets very small, the resistance increases dramatically. A result of the nonlinear reliance of resistance on the radius of the tube can be seen in Figure 4.5. As the mean arterial pressure within a blood vessel is increased, it stretches the vessel and makes the radius, r, larger. Thus larger the radius, the lower the resistance. This is evidenced by the greater blood flows with greater internal pressures. Also shown in Figure 4.5 are two other effects – critical closing pressures and neural stimulation.

Critical closing pressures are due to the fact that the vessel wall has an elasticity and under low pressures the vessel tends to collapse. Also neural stimulation can change the vessel's mechanical properties.

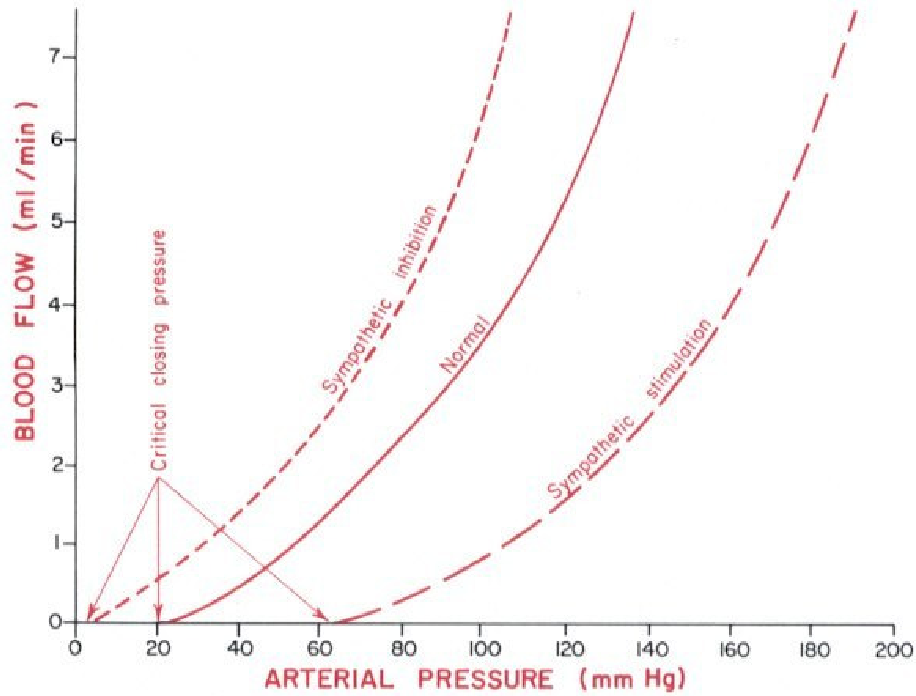

Figure 4.5 Nonlinear Resistance Due to Changes in Radius

Another important property of a blood vessel, in addition to resistance, is compliance. Compliance of a blood vessel can be thought of by a simple example. A balloon that is easy to inflate is said to be highly compliant. That is to say, for a given increase in volume of the balloon, the internal pressure rises very little. A balloon that is not highly compliant will have large internal pressure increases for the same increase in volume. Mathematically, compliance is defined as:

$$C = \frac{\Delta V}{\Delta P}$$

where,

C = compliance, cc/mmHg

ΔV = change in volume, cc

ΔP = change in pressure, mmHg

Figure 4.6 illustrates the concept of compliance. At the start, there is an internal pressure of P_{i1}, and an initial volume of V_1. Then additional volume (ΔV) is injected into the tube, resulting in a new internal pressure of P_{i2} .

Figure 4.6 Compliant Tube

We will assume the outside pressure hasn't changed. The compliance of the tube will be: $C = \dfrac{\Delta V}{(P_{i2} - P_{i1})}$

It must be said that the compliance of a tube is not just dependent on the mechanical properties of the wall. The example below will illustrate this point.

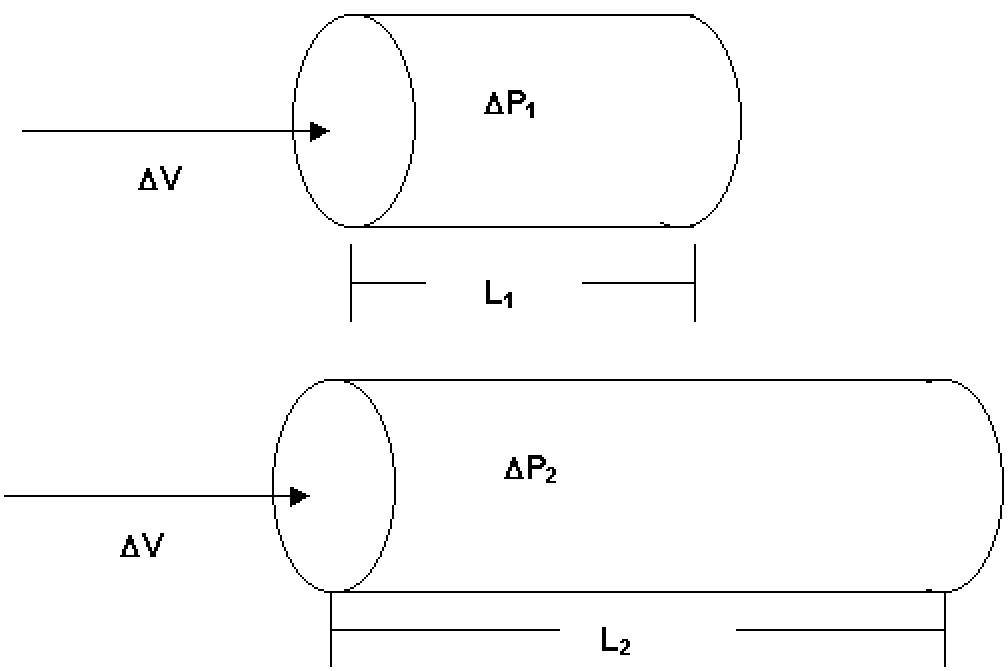

Figure 4.6 Two tubes of equal diameter and wall properties, but different length

Compliance of the shorter tube will be lower than the compliance of the longer tube, because less wall stretch (lower internal pressure) is produced when the same amount of volume is injected into the longer tube. Thus, the volume of the container, in addition to the wall properties, can affect the overall tube compliance. Often times the term elastance is used to describe the tube. Elastance is simply the reciprocal of the compliance.

$$E = \frac{1}{C}$$

For every tube there is a volume required to inject when the tube is initially empty to just begin stretching the wall. This amount of volume is termed "dead volume", V_o. The relationship between pressure and volume for the arterial and venous system in humans is shown in Figure 4. 7.

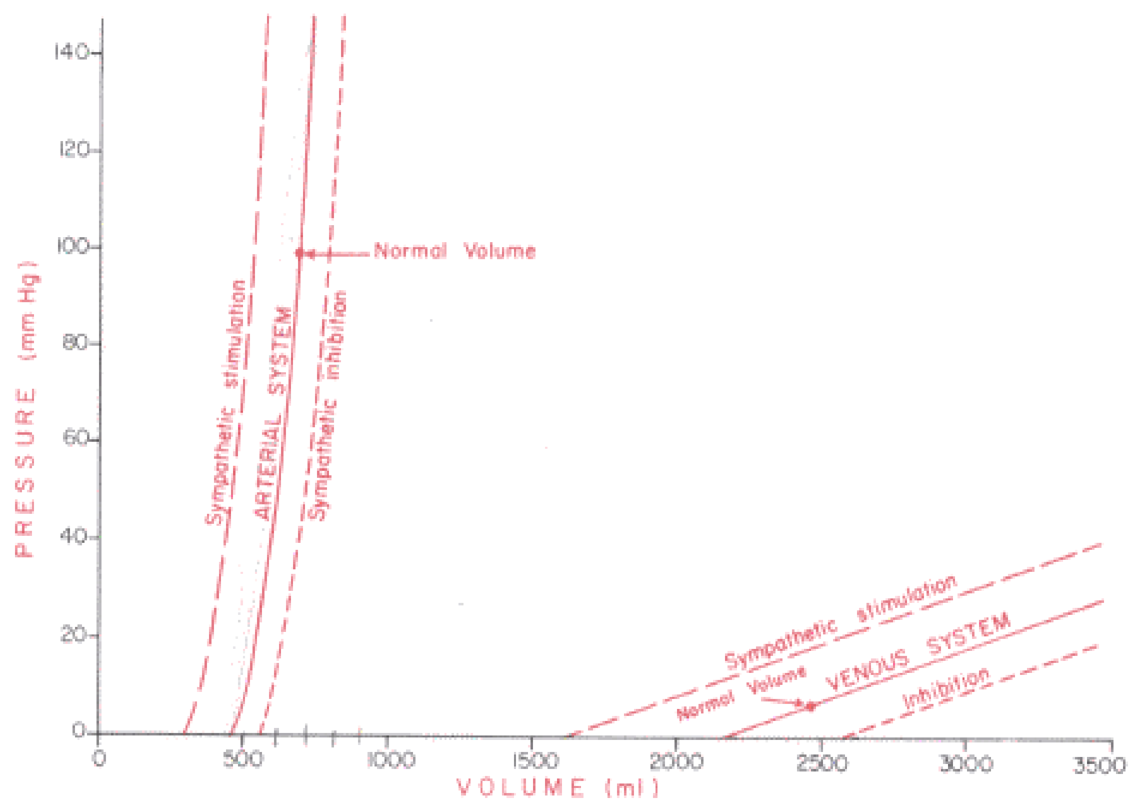

Figure 4.7 Volume-pressure curves of systemic arterial and venous systems

It can be seen that the elastance of the arterial system is much larger than that of the venous system. (The compliance of the arterial system is much lower than that of the venous system). The approximate dead volume of the arterial system is around 400 mL, while the dead volume for the venous system is about 2200 mL.

As we learned earlier in this chapter, the majority of the blood volume is stored in the venous system and this plot bears that out. The elastance (compliance) of the arterial and venous system can be estimated from the slope of the curves. Neural stimulation can change the properties of the vascular system elastance (compliance).

The venous system is highly compliant compared to the arterial system. It appears that the venous system is about 24 times as compliant than the arterial system. That is we can inject (store) more volume into the venous system and have very little pressure rise.

If the heart is arrested (stopped) and the arterial and venous pressures are allowed to equilibrate, a new pressure will be measured and this pressure is termed the mean circulatory filling pressure. It represents the pressure that results when the systemic blood volume occupies both the arterial and venous systems (at the same pressure). The combined compliance of the systemic circulation can be measured under these conditions and as one might expect, the combined compliance is very close to the venous compliance because the venous compliance is so much larger than the arterial compliance (Figure 4.8). Neural stimulation can alter the characteristics of the mean circulatory filling pressure.

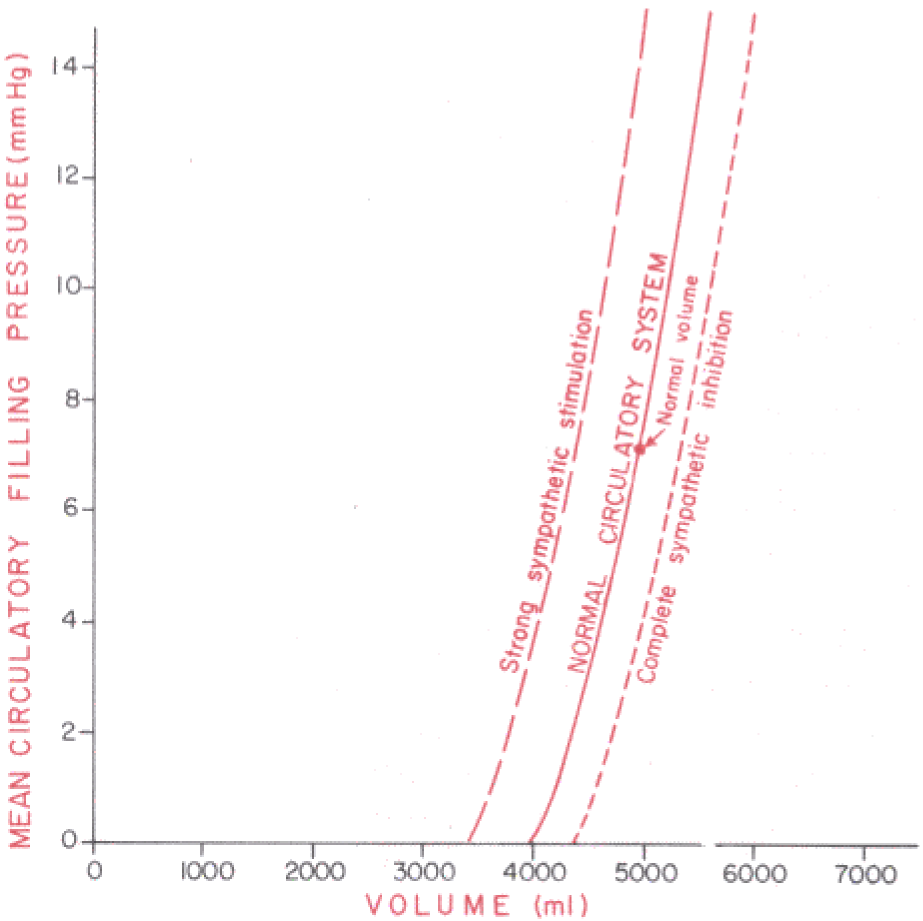

Figure 4.8 Sympathetic Stimulation and Complete Sympathetic Inhibition

Finally, it has been found that the compliance of a vessel is an adaptive property. It appears that a vessel may prefer a certain level of wall stress and will adapt its mechanical properties to achieve it (delayed compliance). Figure 4.9 shows what happens to the internal pressure after a sudden increase in internal pressure and after a sudden decrease in internal pressure. After a sudden change in internal pressure, the vessel tends to change the internal pressure back to "normal" by changing its wall's mechanical properties.

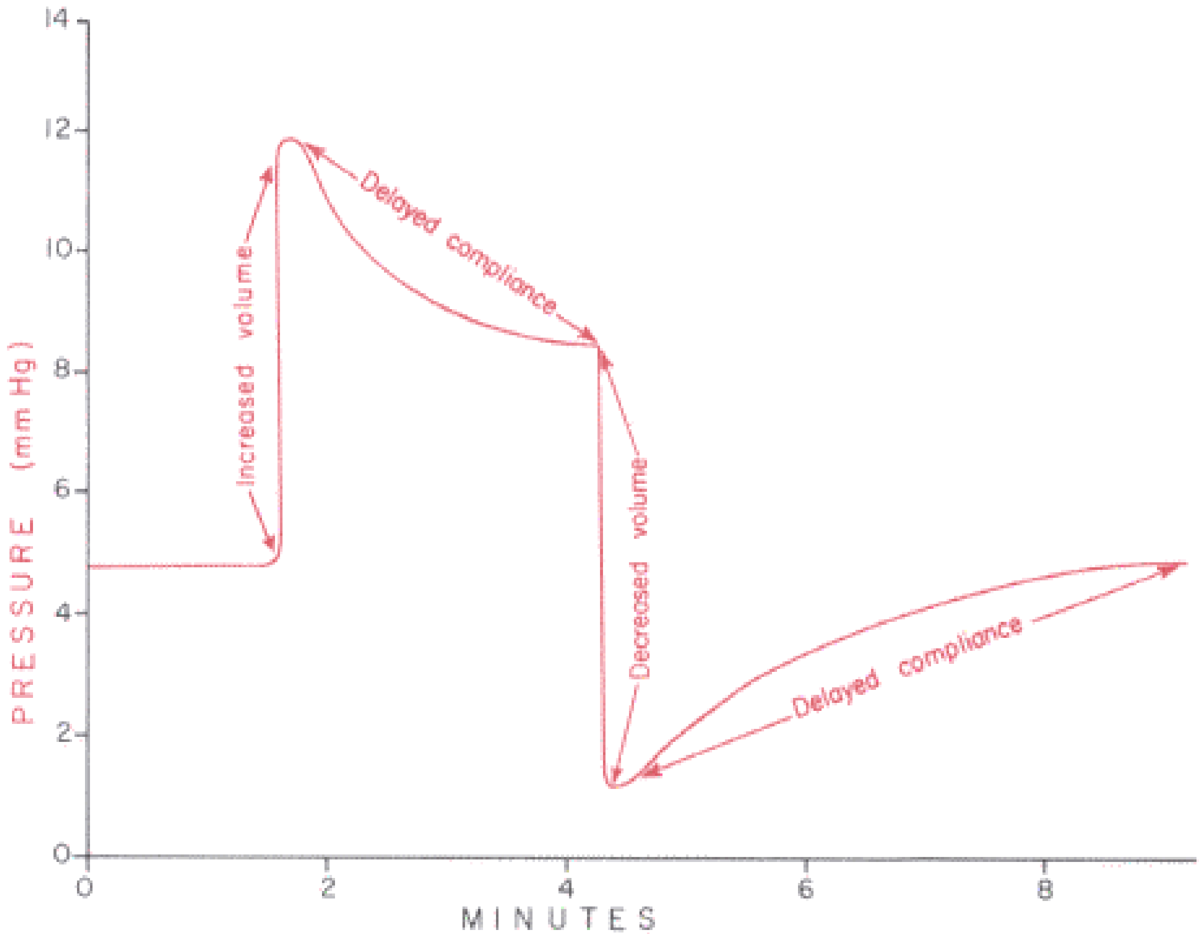

Figure 4.9 Illustration of Principles of Delayed Compliance

An important interaction between venous (right atrial pressure) and the flow output from the heart can be examined in Figure 4.10. If the right atrial pressure is increased from the "normal" operating pressure, the cardiac flow output goes up – as one might hope. If the right atrial pressure goes down, the cardiac flow output also goes down. Right atrial pressure might go up due to too much blood collecting in the venous system and by increasing the cardiac flow output, the volume in the venous system will be reduced and the right atrial pressure will drop, and cardiac outflow will return to "normal" levels.

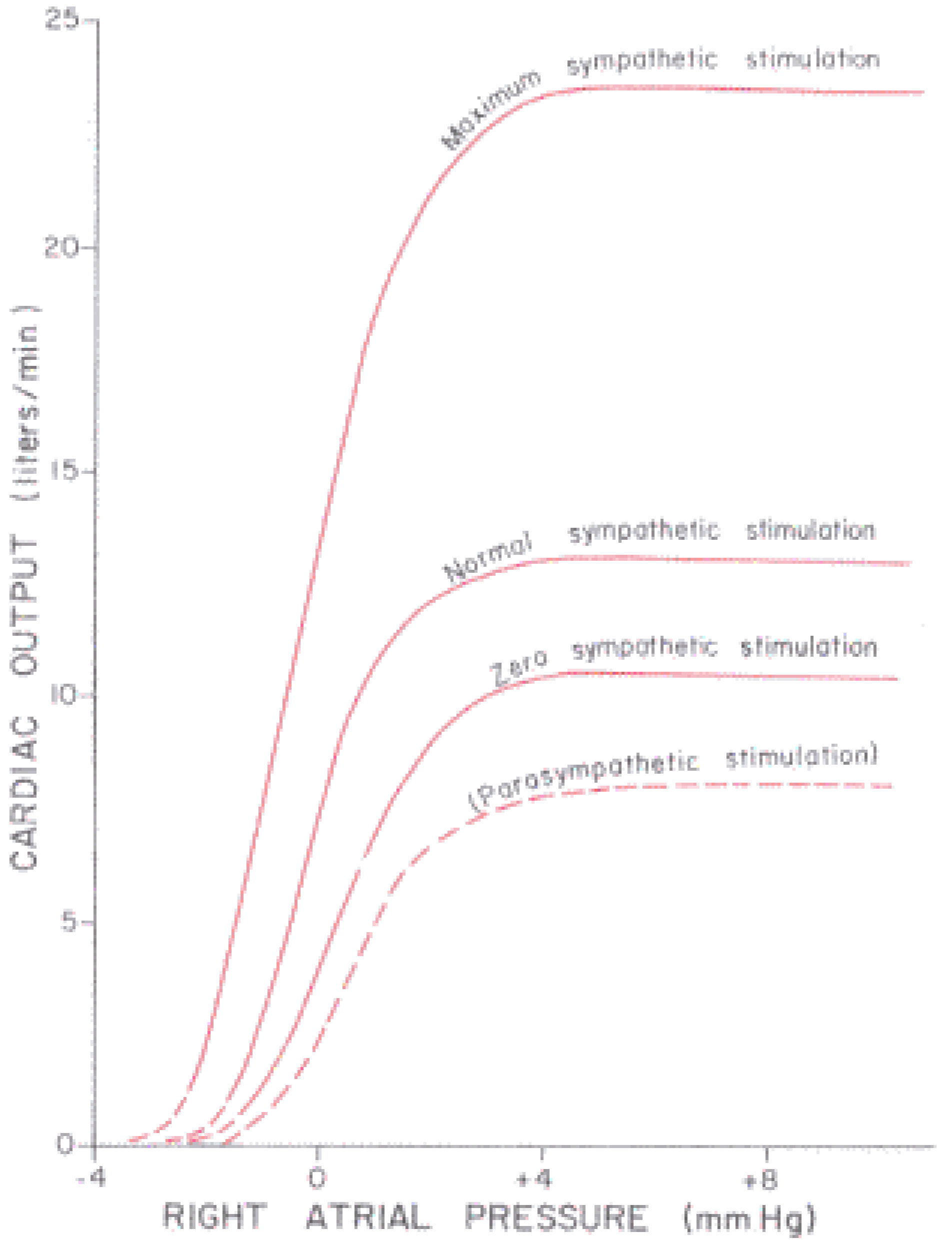

Figure 4.10 Right Atrial Pressure Influence on Heart