INNOVATIONS AND IDEAS

INTEGRATED CARDIOVASCULAR PHYSIOLOGY: A LABORATORY EXERCISE

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Examining the hemodynamic responses to exercise provides a unique opportunity to analyze and integrate cardiovascular physiology because more is learned about how a system operates when it is forced to perform than when it is idle. We designed a laboratory exercise that examines the cardiovascular responses to exercise in a sedentary individual, an athlete, an individual with quadriplegia, and an individual with heart transplantation. The special populations were chosen because of their unique limitations and adaptations, which directly influence cardiovascular function. Basic anatomic and physiological data about the special populations are provided, and the students are challenged to analyze and assimilate information from figures, answer questions, make calculations, and plot graphs. The answers to the questions are provided in the APPENDIX. This laboratory exercise should be attempted in a group to foster discussions and interactions. The laboratory does not require any equipment or software. This exercise should be attempted after the cardiovascular section of the physiology course so that the students can integrate and apply the information presented during the course.


Teaching cardiovascular physiology is a challenge to even the most gifted educator. An enormous amount of information must be disseminated in a relatively short period of time. Traditionally, each cardiovascular component is presented independently, and very little time is scheduled to discuss the interaction between components. In addition, when educators discuss interactions, the system is most often presented as a physical model independent of neural influences. This method of teaching provides limited experience in evaluating and understanding the integrated cardiovascular system, and students do not have the opportunity to apply the concepts. More emphasis should be placed on the application of basic science principles, interpretation of pictorial or tabular material, and problem-solving skills (1). Studying the cardiovascular responses to exercise provides a unique opportunity to integrate and apply the principles of cardiovascular physiology. More is learned about how a system operates when it is forced to perform than when it is idle (3). Therefore, to help students analyze, integrate, and apply basic concepts, we developed a learning tool that evaluates cardiovascular responses during exercise in special populations. The special populations were chosen because of their unique limitations and adaptations, which directly influence cardiovascular function. Therefore, individuals with quadriplegia and heart transplantation were compared and contrasted with sedentary and endurance-trained individuals. Each individual has unique autonomic and physiological control mechanisms regulating cardiovascular function.
To begin this quest of understanding the integrated cardiovascular system, the students are presented with basic anatomic and physiological information about each population. Subsequently, a figure is presented that shows the response of a specific cardiovascular variable during exercise (e.g., heart rate), and the students are challenged to analyze the cardiovascular changes that occur during exercise, keeping in mind the limitations and adaptations present in each individual. The students answer questions, make calculations, and plot data related to that figure. The answers to all the questions are provided in the APPENDIX.

This game should be attempted after completing the cardiovascular section of the physiology course. At this time, the students are prepared to integrate the information assimilated during the section and are ready to apply the information to special populations. The answers do not involve difficult calculations or new information. The purpose of this game was not to provide new information but to help the student apply the information already assimilated and provide insights concerning cardiovascular regulation.

BACKGROUND INFORMATION

The cardiovascular responses during dynamic exercise are examined in four males (age 30 yr, wt 70 kg) with specific limitations or adaptations. The individuals are different in the extent of innervation to their heart and blood vessels, the available muscle mass for exercise, and the efficiency of venous return. The following narrative will describe the unique characteristics of each individual.

Individual With Quadriplegia

The individual with quadriplegia has a transverse spinal lesion at the C5–C8 spinal level, resulting in the loss of sympathetic and motor control below the level of the lesion. However, parasympathetic innervation to the heart is maintained. This individual is limited to arm exercise (arm cycle ergometry), which directly influences the maximum work load, venous return, and cardiovascular function.

Individual With Heart Transplantation

The individual with a heart transplantation can be directly contrasted with the individual with quadriplegia. The donor heart is void of all sympathetic innervation and all significant parasympathetic innervation. However, unlike the individual with quadriplegia, this individual has complete motor function. With complete motor function, this individual has full use of the muscle venous pump and can therefore take advantage of the Frank-Starling mechanism and exercise at a much higher work load.

Sedentary Individual

The sedentary individual has no significant limitations. This individual, of course, has full innervation to the heart and circulation and therefore has cardiovascular responses different from the individuals with quadriplegia and heart transplantation.

Trained Endurance Athlete

The athlete has significant autonomic adaptations associated with exercise training. Exercise training is associated with a higher stroke volume, cardiac output, and oxygen consumption during exercise with no change in the maximum heart rate. In addition, there is a lower heart rate and higher stroke volume at rest. These autonomic adaptations make him uniquely suited to perform exercise, while maintaining homostasis.

THE GAME

Heart Rate

Figure 1 presents the relationship between heart rate and increasing work load. Work load is expressed as the oxygen consumption required to perform the work. Heart rate is under the influence of the autonomic nervous system. Decreases in cardiac parasympathetic efferent activity and/or increases in cardiac sympathetic efferent activity increase heart rate. At the onset of exercise, there is a centrally mediated simultaneous activation of the cardiovascular and motor centers (central command), causing an initial rapid increase in heart rate due to withdrawal of parasympathetic efferent activity. Once heart rate reaches ~100 beats/min, there
is a further increase in heart rate due to activation of cardiac sympathetic efferent activity.

Individuals with heart transplantation and quadriplegia do not have sympathetic innervation to the heart; however, the individual with quadriplegia has cardiac parasympathetic innervation.

Questions
1) Compare the heart rate response to exercise in the individuals with quadriplegia and heart transplantation. How does the absence of cardiac parasympathetic innervation affect the heart rate response to exercise?

2) Compare the maximum heart rate response to exercise in the individuals with quadriplegia and heart transplantation. What accounts for the similarity in maximum heart rate?

3) What factors contribute to the increase in heart rate in the individuals with quadriplegia and heart transplantation?

4) Compare the heart rate response to exercise in the individual with heart transplantation with the sedentary individual. How would the absence of cardiac innervation affect the heart rate response to exercise?

5) Compare the resting heart rate, slope of the increase in heart rate, and maximum heart rate in the sedentary and athletic individuals. How are they different? What accounts for this difference?

Stroke Volume
Figure 2 presents the stroke volume response to increasing work loads in the four individuals. Stroke volume is a function of venous return, cardiac sympathetic efferent activity, circulating catecholamines, and afterload. During exercise, venous return increases because of an increase in the activity of the muscle venous pump. Consequently, end-diastolic volume increases and causes a stronger systolic contraction of the ventricle, in accordance with the Frank-Starling law. During exercise, cardiac sympathetic efferent activity also increases. Stroke volume increases during exercise, reaching a maximum at 40–45% of the oxygen uptake at maximum exercise (V_{O2max}). Finally, stroke volume can also increase slightly because of the effect of circulating catecholamines activating β₁-adrenergic receptors on the myocardium.

Questions
6) Compare the stroke volume responses in the individuals with quadriplegia and heart transplantation. How are they different and what accounts for this difference?

7) Compare the stroke volume response in the sedentary individual with the response in the individual with heart transplantation. What accounts for the similarity in stroke volume?
Questions

10) Compare the cardiac output responses to exercise in the individuals with quadriplegia and heart transplantation. How are they different and what accounts for this difference?

11) Compare the cardiac output responses in the sedentary individual and the individual with heart transplantation. How are they different and what accounts for this difference?

12) Compare the cardiac output responses in the sedentary and athletic individuals. How are they different and what accounts for this difference?

Calculating Oxygen Consumption:
The Fick Principle

The Fick principle (Adolph Fick, 1870) can be written

$$\dot{V}O_2 = CO \times (a-v)O_2$$

where $\dot{V}O_2$ is oxygen consumption, $CO$ is cardiac output, and $(a-v)O_2$ is the arteriovenous oxygen difference. This equation is used to calculate cardiac output or blood flow to any organ. It can also be used to calculate the oxygen consumption of the entire body or any organ, provided the flow rate and the oxygen content of blood samples are known.

Thus oxygen consumed by the body is determined by measuring cardiac output and the oxygen content of the arterial and mixed venous blood. The oxygen saturation of arterial blood with a $P_{O_2}$ of 100 mmHg is ~98%, whereas that of mixed venous blood with a $P_{O_2}$ of 40 mmHg is ~75%. One gram of hemoglobin (Hb) can combine with 1.34–1.36 ml of oxygen. Because normal blood has ~15 g Hb/100 ml, the oxygen capacity of arterial blood is ~20.8 ml oxygen/100 ml blood, and the oxygen capacity of venous blood is ~15.6 ml oxygen/100 ml blood.

Accordingly, oxygen consumed by the body is the product of cardiac output and the arteriovenous oxygen concentration difference.

Question

13) Using Fig. 4 and the Fick principle, calculate the arteriovenous oxygen difference response to exercise in the four individuals. Plot these results in Fig. 5.
Plot the relation between arteriovenous (a-v) oxygen difference and oxygen consumption (question 13).

**Arteriovenous Oxygen Difference**

Figure 6 presents the relationship between arteriovenous oxygen difference and increasing work loads. At rest, oxygen consumption is ~ 250 ml oxygen/min. The arterial (20.8 ml/100 ml)-venous (15.0 ml oxygen/100 ml) oxygen difference is therefore ~ 5 ml oxygen/100 ml blood. As the work intensity increases, oxygen consumption increases. The increased requirements for oxygen are met by increasing cardiac output (delivering more oxygen) and extracting more oxygen from the arterial blood (increasing arteriovenous oxygen difference). Oxygen extraction increases more slowly than cardiac output. The maximum arteriovenous oxygen difference is comparable in the four individuals (~ 16-18 ml/100 ml blood). Because oxygen requirements of the exercising muscles increase significantly during exercise, oxygen extraction in the circulation to the active muscles is nearly complete at maximum exercise.

Questions

14) What accounts for the difference in arteriovenous oxygen difference response to exercise in the sedentary individual and the athlete?

15) What accounts for the difference in maximum oxygen consumption of the sedentary and athletic individuals?

**Myocardial Oxygen Consumption**

Figure 7 presents the relationship between the arteriovenous oxygen difference in the coronary circulation and increasing work loads. Oxygen consumption of the whole heart can be determined using the Fick equation. The oxygen content of venous blood draining the heart is low relative to that of other organs, giving a wide arteriovenous oxygen difference, even under resting conditions. Although the myocardial oxygen extraction increases during severe exercise, this reserve is quite small.

Question

16) Compare arteriovenous oxygen difference response to exercise in the coronary and systemic circulations (Figs. 6 and 7). How are the increased
myocardial oxygen requirements during exercise fulfilled?

Systolic Blood Pressure

Figure 8 presents the relationship between systolic blood pressure and increasing work loads in the four individuals. Systolic blood pressure (pressure during systole, when the heart is active) is the pressure generated by stroke volume during ventricular systole. Systolic blood pressure is a function of left ventricular stroke volume, the peak rate of ejection, vessel wall compliance, and diastolic blood pressure. If one assumes that the compliance of the blood vessels is similar in the four individuals, stroke volume is the major determinant of systolic blood pressure. Differences in rate of ejection and diastolic blood pressure also account for the difference in systolic blood pressure response to exercise in the four individuals.

Questions

17) Compare the systolic blood pressure response to exercise in the individuals with quadriplegia and heart transplantation. How are they different, and what accounts for this difference?

18) Why is the systolic blood pressure response in the individual with heart transplantation lower than that in the sedentary individual?

Diastolic Blood Pressure

Figure 9 presents the diastolic blood pressure response to exercise in the four individuals. Diastolic blood pressure (pressure during diastole, when the heart is at rest) is the pressure exerted by the volume of blood that remains in the arteries after the peripheral runoff of blood from the arteries through the resistance vessels. The arterial blood volume is the net result of the rate of blood flow from the heart to the arteries and the rate of outflow from the arteries through the resistance vessels. Therefore, diastolic blood pressure is a function of heart rate and peripheral vascular resistance. Increases in heart rate increase the rate of inflow of blood and reduce the time during which outflow occurs through the resistance vessels, thereby increasing the diastolic pressure. An increase in the peripheral vascular resistance also causes a decrease in outflow of blood, which results in an increase in diastolic pressure. Normally diastolic blood pressure remains the same or changes only moderately during exercise because although heart rate increases, peripheral vascular resistance decreases. The diastolic blood pressure response to exercise, therefore, depends on the magnitude of the increase in heart rate and decrease in peripheral vascular resistance. Diastolic blood pressure in-

19) Compare the systolic blood pressure response to exercise in the athlete and the sedentary individual. How are they different and why?
creases slightly with increasing work loads in the individuals with heart transplantation and quadriplegia, whereas it decreases in the sedentary individuals and athletes.

Questions

20) Explain the response of diastolic blood pressure to exercise in the athlete and the sedentary individual.

21) What does the rise in diastolic blood pressure with exercise signify?

Mean Arterial Pressure Response

Pulse pressure is the difference between the systolic and diastolic blood pressures. Pulse pressure is a function of the volume of blood ejected by the left ventricle during systole (rapid ejection phase) minus the volume of blood that runs off to the periphery during diastole. The major factors affecting pulse pressure are stroke volume, vascular compliance, and the rate of ventricular ejection vs. the rate of peripheral outflow.

Mean arterial pressure is the average pressure throughout the cardiac cycle. Because systole is shorter than diastole, the mean pressure is slightly less than the value halfway between systolic and diastolic pressures. This is often described as the perfusion pressure or the pressure necessary to maintain adequate blood flow to the tissues. For all practical purposes it is calculated by the formula

$$MAP = DP + \frac{1}{3}PP$$

where MAP is mean arterial pressure, DP is diastolic pressure, and pulse pressure (PP) equals systolic pressure minus diastolic pressure.

Question

22) Using Figs. 8 and 9, calculate the mean arterial pressure response during exercise in the four individuals. Plot these results in Fig. 10. Compare the mean arterial pressure response to exercise in the sedentary individual and the athlete.

Work Units

Work or the energy required to perform work is quantified in a variety of units depending on the situation. It is possible to utilize either units of work, such as kilopond-meters or joules, or units of energy expenditure, such as oxygen consumption (ml/min), kilocalories, or metabolic equivalent terms (METs), because there is a linear relationship between these units. Clinicians are encouraged to understand the relationships between work and energy expenditure because they will be required to utilize these facts in a variety of patient populations. For example, when modifying the activity profile of patients with myocardial infarction, adjusting the insulin requirements of individuals with diabetes, or making nutritional adjustments in obese individuals, the physician must convert the activity or work performed by the patients (activities of daily living) to units of energy expenditure. This process allows the physician to prescribe appropriate medications, dietary restrictions, and activity levels.

Work on a cycle ergometer is conventionally estimated in units of kilopond-meter (kp-m). A kilopond is defined as the amount of force required to accelerate a mass of 1 kg by 9.8 m/s² (gravitational acceleration). Work is force applied over a specific distance. For example, lifting 1 kg vertically through 1 m results in 1 kg·m or 1 kp·m of work. Power is work performed per unit time, so it is estimated in units of kilopond-meter per minute. Work quantified on a cycle ergometer (or other device) can be converted to energy consumption by knowing some basic facts. The oxygen cost of 1 kp-m of work is equal to 1.8 ml of oxygen. To account for the added frictional work on a cycle ergometer, the oxygen

![Graph showing relation between mean arterial pressure and oxygen consumption.](http://advan.physiology.org/)

**Fig. 10**

Plot the relation between mean arterial pressure and oxygen consumption (question 22).
cost of 1 kp·m of work is augmented by 0.2 ml oxygen cost of work against the applied load is 2 ml of oxygen. The total oxygen consumption of an individual working on a cycle ergometer is thus obtained by adding the oxygen cost of work to resting oxygen consumption by the body (~250 ml/min).

\[ \dot{V}_O_2 (ml/min) = 2 ml/(kp\cdot m) \times kp\cdot m/min + 250 ml/min \]

Thus there is a linear relationship between oxygen consumption and work load (2).

Whole body oxygen consumption increases in a linear fashion with increasing work. The oxygen uptake at maximum exercise, termed \( \dot{V}_O_2_{max} \), correlates well with the degree of physical conditioning and has been accepted as an index of total body fitness. The capacity to consume oxygen is related not only to the effectiveness of the lungs but also to the ability of the heart and circulatory system to transport the oxygen and to the body tissue’s ability to metabolize it. The \( \dot{V}_O_2_{max} \) is a reproducible value, especially when corrected for body weight, and it increases with the degree of physical conditioning. In exercise physiology, \( \dot{V}_O_2_{max} \) has been used as a standard of comparison within and across subjects to normalize the effects of various absolute work loads. METs are frequently used to estimate work in clinical cardiology. One metabolic equivalent term is equal to the oxygen consumed by a human being at rest, i.e., 3.5 ml O2·kg\(^{-1}\)·min\(^{-1}\). Various common work loads are quantitated in terms of multiples of oxygen consumption or multiples of METs (dressing and undressing, 2 METs; walking, 3 METs). This serves to guide the patients regarding the work loads that they perform. Thus units of oxygen consumption can be directly converted to METs by understanding the following relationship

\[ MET = \dot{V}_O_2/(weight \times 3.5 \text{ ml·kg}^{-1}·\text{min}^{-1}) \]

where \( \dot{V}_O_2 \) is in milliliters per minute and weight is in kilograms.

The work performed (estimated in terms of kcal/min) also has a linear relationship with oxygen consumption at steady-state, submaximal, aerobic exercise (assuming \( R = 0.82 \))

\[ \text{energy consumed (kcal/min)} = 5 \text{ kcal/l O}_2 \times \dot{V}_O_2 (l/min) \]

**Questions**

23) Examine the relation between \( \dot{V}_O_2, (kp\cdot m)/min, kcal/min, \) and METs presented in Fig. 11. Using Figs. 12 and 13, plot the relationship between

a) METs and kcal/min (Fig. 12)

b) kp·m/min and \( \dot{V}_O_2 \) (Fig. 13)
APPENDIX: ANSWERS TO GAME QUESTIONS

Heart Rate

1) The individual with heart transplantation does not have a rapid rise in heart rate at the onset of exercise because the heart has no significant autonomic innervation. The rise in heart rate is due to the effect of circulating catecholamines. The individual with quadriplegia has an initial rapid rise in heart rate due to the withdrawal of cardiac parasympathetic efferent activity; however, heart rate does not rise further because of the absence of cardiac sympathetic efferent activity.

2) The maximum heart rate responses in the individual with quadriplegia and heart transplantation are similar because the maximum increase in heart rate in both individuals is due to the effect of circulating catecholamines.

3) Factors that contribute to the increase in heart rate in the individual with quadriplegia are withdrawal of the parasympathetic tone and the effect of circulating catecholamines, whereas only the circulating catecholamines contribute to the increase in heart rate in the individual with heart transplantation. At this point it is important to note that circulating catecholamines (norepinephrine and epinephrine) increase heart rate by activating β1-adrenergic receptors on the sinoatrial node.

4) The sedentary individual has an initial rapid increase in heart rate due to withdrawal of cardiac parasympathetic efferent activity and a further increase to an age-dependent maximum due to an increase in cardiac sympathetic efferent activity. There is no rapid rise in heart rate at the onset of exercise in the individual with heart transplantation because of absence of cardiac parasympathetic innervation; the rise in heart rate occurs because of the effect of circulating catecholamines.

5) Autonomic adaptations associated with chronic endurance training result in an enhanced cardiac parasympathetic efferent activity, and therefore the athlete has a resting bradycardia. Note that the heart rate response at similar work loads is lower in the athlete compared with the sedentary individual.
however, both individuals achieve a similar age-dependent maximum heart rate.

Stroke Volume

6) The individual with quadriplegia has no motor control below the level of the lesion (no muscle venous pump), and therefore venous return does not increase with exercise. In contrast, the individual with heart transplantation is able to increase stroke volume because of a functioning muscle venous pump. This illustrates the importance of the Frank-Starling mechanism. In fact the individual with heart transplantation has a stroke volume comparable to that of the sedentary individual.

7) Stroke volume response to exercise is determined by end-diastolic volume, cardiac sympathetic efferent activity, circulating catecholamines, and afterload. The muscle venous pump is functioning normally in both individuals, and therefore the stroke volume response to exercise is initially similar; however, the maximum stroke volume achieved in the individual with heart transplantation is lower because of the absence of cardiac sympathetic efferent activity.

8) The athlete has a much higher stroke volume at similar work loads. The athlete has a larger ventricular volume and slower heart rate, which allows for a greater cardiac filling during diastole (greater end-diastolic volumes); therefore the stroke volume response in the athlete is much greater compared with that of the sedentary individual.

Cardiac Output

10) The individual with quadriplegia has a very low cardiac output because stroke volume does not increase with exercise (no muscle venous pump). In addition, because of the reduced muscle mass, the individual with quadriplegia has a reduced ability to increase total body oxygen consumption. In contrast, the individual with heart transplantation has a normal muscle venous pump and muscle mass; therefore venous return is enhanced, and total body oxygen consumption significantly increased. Note that both individuals have a limited heart rate response to exercise (absence of cardiac sympathetic efferent activity). The lower cardiac output response in the individual with quadriplegia is therefore due to a severely limited stroke volume, heart rate, and muscle mass.

11) The cardiac output responses to exercise are initially comparable in the sedentary individual and the individual with heart transplantation; however, at work loads above 45% of \( \dot{V}O_{2 \text{max}} \), the cardiac output response is lower in the individual with heart transplantation because of the poor heart rate response to exercise.

12) Cardiac output in the sedentary individual and the athlete are similar at lower work loads. Even though the athlete has a lower resting heart rate (Fig. 1), he has a much higher stroke volume (Fig. 2) at the same work load, and therefore cardiac outputs are similar. Note, however, that because of large stroke volumes in the athlete, he can achieve a much higher cardiac output (nearly double) compared with the sedentary individual.

13) Arteriovenous Oxygen Difference

14) Up to 75% of \( \dot{V}O_{2 \text{max}} \) of the sedentary individual, the arteriovenous oxygen difference of the sedentary and athletic individuals is similar. However, above this work load, the arteriovenous oxygen difference is lower in the athlete compared with the sedentary individual because the athlete has much higher cardiac output. Thus the athlete is able to meet the increased oxygen requirements of the body by increasing cardiac output without significantly altering arteriovenous oxygen difference homeostasis.

15) Even though the athlete and the sedentary individual have the same maximum arteriovenous oxygen difference, the difference in the \( \dot{V}O_{2 \text{max}} \) is due to the difference in the cardiac output between the two individuals. Actually cardiac output is the factor limiting the maximum exercising capacity.

Myocardial Oxygen Consumption

16) Under resting conditions, the arteriovenous oxygen difference in the coronary circulation is 12–14 ml/100 ml compared with 4–5 ml/100 ml in
the systemic circulation. In response to exercise the maximum arteriovenous oxygen difference in both circulations is similar (16–18 ml/100 ml). Thus the coronary circulation has a very small reserve for extracting oxygen. Therefore the increased myocardial oxygen demands during exercise are primarily met by increases in the coronary flow.

Systolic Blood Pressure

17) The systolic blood pressure response in the individual with quadriplegia is much lower than that in the individual with heart transplantation because of the poor stroke volume response to exercise. The reduced stroke volume response to exercise is due to the failure of cardiac performance to increase resulting from an absence of the muscle venous pump and reduced muscle mass.

18) The systolic blood pressure response to exercise is lower in the individual with heart transplantation compared with the sedentary individual because of a lower stroke volume response to exercise (absence of cardiac sympathetic efferent activity).

19) The athlete has a much higher systolic blood pressure response to exercise than the sedentary individual because of a larger stroke volume and a more rapid rate of its ejection.

Diastolic Blood Pressure

20) Diastolic blood pressure decreases in response to exercise (despite the increase in heart rate) because of a decrease in the total peripheral resistance. Total peripheral resistance will decrease because of metabolic vasodilatation. Total peripheral resistance can decrease more in the athlete because the athlete has an increased cardiac performance and much higher systolic pressure, which maintains perfusion pressure. During exercise, perfusion pressure is monitored and maintained by the arterial baroreflex and muscle metaboreflex. If cardiac performance is not adequate enough to maintain perfusion pressure, the arterial baroreflex and muscle metaboreflex reflexly increase total peripheral resistance. Therefore, the heart works against a decreased afterload. This is a major advantage to the athlete.

Work Units

23) It can be seen from Fig. 11 and the equations following it that there are linear relationships between the units used to quantify work: oxygen consumption, METs, kp·m/min and kcal/min. One liter of oxygen consumed per minute is equivalent to 426.85 (kp·m)/min, 5 kcal/min, and 4.08 METs.

SUMMARY

This game was designed as a laboratory exercise to help students apply basic principles of cardiovascular physiology, assimilate information from graphs,
and understand the integrated cardiovascular system. It requires pencils, paper, an interest in cardiovascular physiology, and 3 h to complete.

We suggest that students work in groups of four or five to foster discussion and interactions. This would stimulate an exchange of information, and the questions will make the discussion thought provoking.

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References


3. Rowell, L. B. Human Circulation Regulation During Physi-

Suggested Readings


Teachers and their students may find the following articles from News in Physiological Sciences useful when exploring the physiology of the preceding paper:


