CONCEPTS in SHOCK

Understand the pathophysiology to better serve your patients

By Paul E. Phrampus, MD

myWebCE CONTINUING EDUCATION ARTICLE

CASE 1: You're rushing a 43-year-old male driver from an overturned vehicle to a local trauma center. He complains of severe pain in his abdomen and left femur, which is obviously deformed. His skin is cool, clammy and sweaty, and he has a blood pressure of 118/72, heart rate of 130 and respirations of 26.

CASE 2: You're called to the home of a 77-year-old female with a four-day history of cough and fever. She's confused and has warm, dry skin. Her breathing is labored. *Vital signs:* blood pressure 110/80, heart rate 118 and respirations 30.

CASE 3: You respond to a 28-year-old male, unconscious and gasping for breath on the ground next to a lawnmower. Neighbors report that he has suffered multiple bee stings. He has obvious airway swelling, and his tongue is protruding from his mouth. He is deeply cyanotic. *Vital signs:* a heart rate of 40 and blood pressure of 50 palp.

CASE 4: You're called to a local pool after a
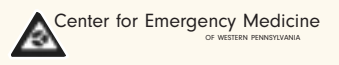
Objectives

- Describe the processes of aerobic and anaerobic metabolism.
- Review the role of various compensatory mechanisms the body employs to maintain blood pressure.
- Explain the difference between hypovolemic and distributive shock, and give examples of each.

17-year-old male dove into the shallow end head first. He has minimal movement of his arms and no movement of his legs. He complains of severe neck pain and difficulty breathing. His blood pressure is 80/50, heart rate 88, respirations 12 and shallow.

Introduction

The patients in the above cases vary considerably in their presented history and situations, but they all share one common theme: They're all in shock. **Shock** is a condition that exists when one or more end organs have a state of impaired **perfusion**. Causes vary widely, as demonstrated above.

The underlying pathophysiology of the different types of shock all share common pathways of attempted compensation, such that the body tries to maintain blood pressure at all costs. Sensitive organs, such as the brain and the heart, have altered function within seconds to minutes if perfusion is compromised.

Without rapid intervention and treatment, uncompensated shock has a high mortality. To effectively recognize and begin treatment of a patient in shock, and help prevent **uncompensated shock**, you must recognize early signs and symptoms.

This article reviews the basic physiology associated with the body's attempt to compensate for shock. We begin with an overview from the system level and then review basic cellular physiology to demonstrate how many of the changes involved with shock occur. After a review of the physiology of compensation, we look at various categories of shock and the specific pathophysiology that accompanies each to formulate an effective initial treatment plan.

Anatomical review

To begin a discussion about shock, we need to consider fluid distribution within the body. During normal body function, fluids shift between the intravascular, intracellular and interstitial spaces to maintain **homeostasis**: Intracellular fluid is contained within cells, interstitial fluid is located in the space between cells, and, for the purposes of this discussion, we'll assume the intravascular space, including the blood vessels and heart, contains mostly blood and plasma.

The basic function of the blood is to carry oxygen to all of the body's cells and transport carbon dioxide back to the lungs to be expelled during expiration. Plasma can be thought of as the fluid in which blood cells float.

The discussion of normal physiology will focus largely on the intravascular space because measurements of that compartment reflect the overall status of body fluid balance. A review of the anatomical make-up of the intravascular space begins with the heart.

The heart is the chief organ of the intravascular space. It's a side-by-side, two-stage pump that provides the forward flow of fluid. The right side of the heart receives flow from

Glossary

Aerobic metabolism: The process of cellular work being accomplished in the presence of adequate oxygen.

Anaerobic metabolism: The process of cellular work being accomplished without adequate oxygen.

Baroreceptors: Pressure receptors in the wall of the atrium, the vena cava, aortic arch and carotid sinus that are sensitive to stretching of the wall, which occurs with increased pressure.

Cardiac output: The volume of blood pumped by the heart in one minute; determined by heart rate multiplied by stroke volume.

Chemoreceptors: Cells located in the carotid arteries, the aortic arch and the brain's respiratory center that detect concentrations of oxygen and carbon dioxide in the blood.

Diastolic blood pressure: The pressure exerted on artery walls when the heart is in the relaxation phase.

Histamine: A pharmacological agent, released by mast cells, that promotes inflammation.

Homeostasis: A state of equilibrium in the body.

Perfusion: The process of circulating blood to the organs, delivering oxygen and removing wastes.

Mast cells: Cells of connective tissue that release histamine, which is responsible for the inflammatory response.

Mitochondria: A small organ inside a cell responsible for energy production and cellular respiration.

Peripheral vascular resistance: The total resistance against which blood must be pumped.

Shock: Inadequate tissue perfusion.

Stroke volume: The amount of blood pumped out of a ventricle with each contraction.

Systolic blood pressure: The pressure exerted on artery walls during the contraction phase of the heart.

Tachypnea: An abnormally rapid respiratory rate.

Uncompensated shock: The severe state of shock in which hypotension has occurred despite the body's attempts to compensate.

Hemorrhagic shock most often occurs in response to traumatic injury and results in an acute loss of blood and body fluids.

the body's periphery and pumps largely deoxygenated blood to the lungs to exchange carbon dioxide for a new supply of oxygen. Freshly oxygenated blood is returned to the left side of the heart, which pumps at a higher pressure and empties into the aorta, the largest artery in the body. From there begins a progressive branching of smaller arteries.

These smaller arteries branch into tiny vessels called arterioles, which then connect directly to the microscopic capillaries. Red blood cells pass single file through the capillaries, releasing oxygen in exchange for carbon dioxide released from the cells as a waste product of cellular metabolism.

Heading back to the heart, the capillaries are connected to small vessels called venules, which combine to form tubular structures called veins. Veins from the lower body join to form the inferior vena cava. Veins from the superior aspect of the body join to form the superior vena cava.

The superior and inferior vena cava meet at the right atrium, which is the first heart chamber to receive deoxygenated blood from the body. The blood is pumped from the right side of the heart to the pulmonary circuit through the lungs to exchange carbon dioxide and oxygen. Then it flows back to the left side of the heart to complete the circuit. It's helpful to think of the intravascular space as a closed loop system as we describe the mechanisms of maintaining blood pressure.

Blood pressure physiology

Blood pressure is a measurement of fluid pressure in the intravascular space. Usually it is measured at a point close to the heart, often at the brachial artery. Blood pressure is usually represented as two different numbers. The first number, **systolic pressure**, indicates the pressure at it's maximum, when the left heart is fully contracted. The second number, **diastolic pressure**, is a measurement that reflects the lowest pressure in the system, which is when the left heart is most relaxed. For the purposes of perfusion, a more useful concept is *mean arterial pressure*, the average pressure in the system over the entire cycle of the heart. (For an in-depth discussion of blood pressure, see "BP primer," February 2004 *JEMS*.)

Blood pressure is a function of several individual components of the vascular space. First, to maintain pressure, the heart must be pumping blood into the system. This amount is chiefly influenced by the heart rate (HR), or the number of times the heart beats per minute, and the **stroke volume** (SV), the amount of blood the heart pumps with each contraction. The pumped blood combined over time equals the **cardiac output** (CO), which is equal to HR x SV.

A major mechanism that keeps blood pressure constant is the body's ability to control the HR (either increasing it or decreasing it), as well as the strength of the contractions that essentially raise and lower the SV.

For pressure to remain unchanged, the space of the vascular compartment must remain constant, assuming that the other factors involved in the system remain unchanged. If the size increases dramatically, there won't be enough fluid in the system, and pressure will fall. Conversely, if the size of the intravascular space decreases, pressure rises. The overall size of the vascular space is termed **peripheral vascular resistance** (PVR). PVR is a reflection of the amount of resistance blood vessels provide for the heart to pump fluid against. This is an important concept because blood vessels can constrict, effectively causing a higher PVR. This occurs by essentially making the vascular space smaller. This is another mechanism the body uses when attempting to maintain a constant pressure in response to change. Thus, blood pressure essentially reflects cardiac output times the PVR.

Control over individual components of the blood pressure equation is complex and performed by many systems. The central nervous system (CNS) plays a major role. Areas at the base of the brain (the vasomotor center) help to control the amount of peripheral vascular resistance. The sympathetic nervous system can cause an increase in both heart rate and the force of contraction of the heart.

The body responds to stress by employing various methods of compensation—adjusting heart rate and stroke volume of peripheral vascular resistance—to maintain blood pressure within a normal range. The central nervous system also coordinates the continuous monitoring of these factors and responds to alterations in the body's hemodynamic state that impair, or threaten to impair, end-organ perfusion.

Hemodynamic status monitoring occurs in several areas. Two well-known hemodynamic monitoring systems are baroreceptors and chemoreceptors. **Baroreceptors**, located in the arch of the aorta, the carotid arteries and the walls of several large arteries, provide information to the CNS regarding pressure in the

vessel walls. This information is used to direct compensation mechanisms to help maintain or restore blood pressure. **Chemoreceptors** are located in the aortic arch and the carotid arteries, and in the respiratory center of the brain. They provide information on circulating levels of oxygen, carbon dioxide and blood pH.

Another monitoring system is the brain's frontal cortex, the area where cognitive thoughts are processed. The sympathetic nervous system can be activated by a visual image via networks involving several areas of the brain. *Example:* If someone saw a gun pointed at them, they would begin to have physiologic changes (such as increases in heart rate and peripheral vascular resistance) before any blood loss occurs. The same goes for vigorous exercise. The thought of beginning strenuous exercise causes a similar set of changes before the activity begins.

Cellular physiology

Reviewing some basics of cellular physiology is important to understanding the body's response to shock. The cell is the smallest functional unit of the body. The millions of cells in the human body are the building blocks that make tissue. Tissues combine to form organs.

Even though cellular metabolism is complex, it can be simplified for this discussion of shock with a description of basic energy requirements and metabolism demands. Car engines serve as a good analogy for cellular metabolism. A car engine requires a mixture of air and gasoline to function. When a car is properly tuned, it functions efficiently with a minimal amount of waste (exhaust). An out-of-tune car may still work, but produces more waste for the same amount of work as a properly adjusted car would. In much the same way, all cells require an energy source, perform some sort of work and produce waste products.

Those energy sources are glucose and oxygen. Inside the cell is a specialized unit called the **mitochondrion**, which produces energy for the cell. If the cell receives the proper amounts of oxygen and glucose, the mitochondria function effectively, with minimal waste products. The primary waste product of cellular work is carbon dioxide, a weak acid. The body easily controls this small amount of acid. It is generally expelled via expiration in the lungs, a process called **aerobic metabolism**.

When cells don't receive enough oxygen, the mitochondria switch to a less efficient process called **anaerobic metabolism**. Although the cell may still be able to work, it does so with less strength and efficiency and produces more waste. Cells functioning with anaerobic metabolism not only produce more carbon dioxide, they produce lactic acid, a waste product that can cause acidosis in the bloodstream. Accumulating acid in the bloodstream begins to cause

Aeromedical transport may be indicated for any condition affecting perfusion of vital organs—not just for hemorrhagic shock.

impaired functioning in other cells. The chemoreceptors described above sense this drop in pH, or worsening acidosis of the circulating blood.

Compensation mechanisms

The human body has evolved to attempt to maintain blood pressure at all costs. Thus, elaborate compensation mechanisms have developed. Understanding the physiology of the compensatory mechanisms and their effect on the body will help you to recognize shock earlier. Providing early interventions for compensated shock can mean the difference between life and death for your patient.

Signs and symptoms of shock can range from mild in minor cases to serious derangements in level of consciousness and vital signs in life-threatening cases. The severity of the symptoms relates directly to the severity of the shock.

The cardiovascular system is among the fastest acting compensatory systems. This is readily observable on physical examination. Early in a state of compensated shock, the vasomotor center and the sympathetic nervous system are likely active in compensation.

Signs of cardiovascular compensation include tachycardia from both the nervous system's influence on heart rate, as well as increasing levels of carbon dioxide. Also, changes in skin color may occur as peripheral vascular resistance increases. Skin may become pale as blood is shunted away from the skin surface to preserve blood flow to more vital organs, such as the heart, brain and liver. The sympathetic nervous system may also activate sweat glands, resulting in diaphoresis.

You will often observe **tachypnea**.

This contribution of the respiratory system results in part from the anxiety related to the situation, which can range from mild anxiousness to combative, agitated behavior. More importantly, while the sympathetic nervous system is activated, cell work increases significantly. *Example:* Cardiac cells contract harder and faster and produce more carbon dioxide, which must be cleared via exhalation. In severe states of shock, acidosis may occur from the accumulation of lactic acid, further stimulating the respiratory system via chemoreceptors.

A complex system of compensation involving several other major organ systems, called the neuro-endocrine pathway, is also activated. The sympathetic nervous system activates the adrenal glands to secrete the hormones epinephrine and norepinephrine, which cause significant vasoconstriction and further increase cardiac activity. Additionally, epinephrine stimulates the pancreas to

release glucagon into the bloodstream, causing the liver to secrete stored glucose into the bloodstream. This response is important because increased cellular activity requires higher levels of circulating glucose. Critically ill patients in shock often exhibit mildly elevated blood glucose levels.

Several other compensatory systems help the body maintain or restore a proper state of fluid balance. As blood pressure falls, the renal system secretes the hormone renin. Once in the circulation, renin is converted to angiotensin II, a potent

Treatment for most forms of shock includes the administration of normal saline or a colloid solution. How much fluid to give is now being studied.

vasoconstrictor that helps restore blood pressure to normal levels. Angiotensin II also stimulates the release of aldosterone from the adrenal gland. Aldosterone stimulates the kidneys to retain sodium, causing body fluid retention.

The posterior pituitary gland in the brain releases an antidiuretic hormone in response to a rise in the osmotic pressure of the circulation, stimulating the uptake of free water in the kidneys. This causes the kidneys to retain fluid by making urine more concentrated.

As the state of shock becomes more severe, compensation mechanisms become overwhelmed, and uncompensated shock occurs. A significant contributor of circulatory collapse is acidosis. Acidosis worsens as various compensatory mechanisms require more and more oxygen and glucose, overwhelming the mitochondria, which begin anaerobic metabolism and cause increased release of lactic acid.

Other molecular mechanisms involving inflammatory proteins and the formation of nitric oxide (NO) also contribute to the failure of compensating mechanisms and further acidosis. Severe acidosis inhibits the ability of muscle, including cardiac muscle, to contract. Once the heart cannot maintain adequate output, death quickly results.

Once hypotension occurs in the patient in shock, mortality is high, regardless of the underlying cause. After reviewing the physiology, you must classify the shock to begin rendering appropriate care. This is the area in which the physiology of the pathways differs some.

Types of shock

Two broad categories of shock are generally recognized: *hypovolemic* and *distributive*. Hypovolemic shock represents the overall loss of fluid, while distributive shock represents no change in overall body fluid, but a problem of distribution within the three compartments.

Hemorrhagic shock is the classically studied shock. It usually occurs in response to traumatic injury and results in an acute loss of blood and body fluids via bleeding. Acute blood loss causes the patient to progress through the entire spectrum of shock, as described above, relative to the severity.

Treatment: Stop the bleeding and restore lost fluids, either with crystalloid fluids, such as normal saline, or colloid solutions, such as blood. How to care for injuries that cause internal bleeding that cannot be stopped in the field is controversial. The question of whether to aim for a normal blood pressure vs. an adequate blood pressure to ensure perfusion of the brain is currently under investigation.

Septic shock is caused by an overwhelming infection of a microbial organism. It frequently represents a combination of hypovolemic and distributive processes. Often, in-

fection causes decreased appetite and lethargy and decreased fluid intake. This, combined with fever, sweating and tachypnea, can lead to severe dehydration or a hypovolemic state. It can also be accompanied by significant electrolyte abnormalities that impair organ function.

A hypotensive patient with anaphylaxis also requires massive volumes of fluid to restore the fluid in the intravascular space.

Additionally, in some forms of septic shock, the infecting bacteria release toxins that not only cause vasodilation, but also impede vasoconstriction. This significantly impairs the compensating mechanism's ability to maintain normal blood pressure.

The initial treatment of septic shock includes fluid replacement and the simultaneous use of vasopressor agents, such as dopamine, to help overcome the vasodilation caused by circulating toxins. Medications, such as antibiotics in the case of a bacterial infection, are also necessary to treat underlying infection.

Anaphylactic shock represents a type of distributive shock. In response to an allergic stimuli, there is a massive release of **histamine** from **mast cells**. The result is significant vasodilation that rapidly leads to hypotension. The histamine release also causes capillary membranes to leak massive amounts of fluid from the intravascular compartment. This causes a sudden surge in the fluid volume of the interstitial space, resulting in massive subcutaneous tissue swelling. Of most concern is the significant swelling that occurs in the neck and throat region that can close off a patient's airway in a matter of minutes.

Initial treatment of anaphylactic shock is directed at keeping an open airway, with simultaneous injections of epinephrine to help restore the the ability of capillary membranes to maintain fluid and, thus, contribute to vasoconstriction. Administration of diphenhydramine is critical to help reverse the effects of the histamine release.

A hypotensive patient with anaphylaxis also requires massive volumes of fluid to restore the fluid in the intravascular space, which is significantly depleted despite the body's outward appearance, which would seem to indicate massive volume overload.

Neurogenic shock is caused by a high spinal cord injury, which results in the inability of sympathetic nervous system signals to maintain vasoconstriction, resulting in further hypotension. Additionally, the mechanisms that normally cause cardiac compensation fail, resulting in a peculiar presentation of shock in which the patient has hypotension with no tachycardia. The skin is often warm and well-perfused, as compared with the normal shock presentation of cold and clammy. This presentation is caused

by the loss of sympathetic input that normally causes the blood to be shunted away from the skin surface to conserve pressure. Patients usually present with a severe neurologic finding, such as an inability to move their arms and legs.

Spinal shock treatment is restoration of pressure by the infusion of crystalloid fluids. This typically restores blood pressure to maintain brain function. Occasionally, a vasopressor, such as IV norepinephrine, is used to cause direct vasoconstriction.

Cardiogenic shock, a result of direct failure of the pump, carries very high mortality. It occurs when the heart can't effectively pump the circulation needed to maintain blood pressure and flow through the circulatory system. It may result from a direct cause, such as ischemia from a massive heart attack, or secondary to advanced uncompensated shock from substantial acidosis. As cardiogenic shock progresses, pulmonary edema may de-velop from increased pressures in the pulmonary circulation, causing fluid to leak into the alveoli of the lungs.

Initial treatment for cardiogenic shock is crystalloid fluid infusion to increase flow through the circulatory system by increasing the pressure of venous return to the right side of the heart. Heart selective vasopressors, such as dobutamine, may be used to attempt to increase the force of contractions and the rate of a failing heart.

Conclusion

The physiology of the circulatory system is designed to try and maintain blood pressure at all costs. The compensating mechanisms are extensive and complex. Understanding the basic processes involved in compensation helps clue in the provider to the proper diagnosis of shock.

Uncompensated shock occurs when the body is successfully maintaining pressure via the use of these stabilization pathways. Rapid interventions are important to try and prevent the progression to uncompensated shock, signified by hypotension. Uncompensated shock has significantly high mortality rates in the absence of rapid, corrective interventions. JEMS

Paul E. Phrampus, MD, is an assistant professor in the department of emergency medicine at the University of Pittsburgh. He is the medical director of Fayette EMS and a frequent lecturer and author on EMS topics. He is a former paramedic who has been involved in EMS since 1981. He can be reached via e-mail at p.phrampus@comcast.net.