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FLUID DYNAMICS - HOW IT TEACHES US ABOUT AIR-FLOW IN THE LUNGS

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Many respiratory therapy students and practitioners alike have grappled over such fluid physics models as the law of continuity, the Bernoulli principle, and the Venturi effect. These three concepts of fluid physics will be discussed from theoretical and from a clinical perspectives.

The law of continuity, or the continuity equation, to which it is sometimes referred, is founded on the law of conservation of matter. The law of conservation of matter states that the mass of substances in a closed system will remain constant, regardless of what processes are acting inside the system. In other words, matter may change form, but it can neither be created nor destroyed in an isolated system. For example, if an incompressible fluid flows in laminar fashion at a constant flow through a tube, the law of continuity applies. In such a model, the flow into the system must equal the flow out of the system.

> ***Physiologically, the law of continuity applies to the flow of air through the lungs***

Let's consider a funnel-shaped tube whose diameter decreases along its length, and has a fluid moving through it at a constant flow. The portion of the tube where the flow enters is wider than the section where the flow exists. Between these two points, is a narrowing, or constriction. The volume of fluid flowing through the tube per time is deemed constant. The aforementioned considerations encompass the continuity equation, which states that the cross-sectional area (A = cm2) of a tube through which an incompressible fluid flows at a constant rate is inversely related to the velocity (v = cm/sec) of the flow ($\dot{V}$ = cm3/sec). That is,

cross-sectional area x velocity = flow

$$A \times v = \dot{V}$$

cm2 x cm/sec = cm3/sec

What happens in this system is the velocity of the flow increases when the flow moves through the narrowed portion of the funnel-shaped tube. At that location, the cross-sectional area decreases and the velocity of the flow increases. Because the flow is constant in this system, the product of the cross-sectional area and the velocity anywhere along the tube will equal the cross-sectional area times the velocity at any other point in the tube. That is,

A1 x v1 = A2 x v2

The fluid exits the system at a higher velocity than upon entering it. Recall the days when you attempted to spray a childhood friend with water from a garden hose in the backyard. With the opening of the hose unobstructed, water leaves the hose with a low velocity, and a stream of water extending only a few inches. However, when you partially obstruct the opening of the hose with your thumb, water leaves at a much higher velocity, sending out a stream several feet to douse your playmate. (You employed the law of continuity well before you became a therapist.)

Physiologically, the law of continuity applies to the flow of air through the lungs. During inspiration, air flows through the trachea which has a cross-sectional area ranging from 3.0 to 5.0 cm2. After the tracheobronchial tree divides along 23 generations, the gas exchange region achieves a cross-sectional area of approximately 700,000 cm2. The velocity of the inspired flow decreases from what is characterized as bulk convective flow in the large airways to molecular diffusion in the alveoli.

Conversely, during exhalation cross-sectional area decreases and the velocity of the flow increases. Interestingly, a normal adult can generate an exhaled air velocity of around 500 mph during an explosive cough. Relative to the lung, the continuity equation can also be expressed as follows:

Atrachea x vtrachea = Aalveoli x valveoli

The Bernoulli principle explains the relationship between the velocity of the flow and the lateral wall pressure for an incompressible fluid flowing at a constant flow in laminar fashion through a tube. Note that the continuity law described the same relationship between the velocity of the flow and the cross-sectional area. The lateral wall pressure is the pressure exerted against the walls of the tube. The lateral wall pressure radiates 360 degrees from the center of a horizontally flowing fluid to the internal aspect of the walls of the conduit. The Bernoulli principle is based on the law of conservation of energy, which asserts that in any system energy can neither be created, nor destroyed; however, energy can be transformed. Therefore, the total energy in the system remains constant.

The Bernoulli principle holds that the sum of the kinetic energy (1/2 Dv2), pressure (lateral wall pressure) energy (P), and potential energy (Dgh) at any point in the system equals the sum of those three forms of energy at any other location in the system. Quantitatively, the Bernoulli equation is

$$\left(1/2Dv^2\right) + P_1 + Dgh_1 = \left(1/2Dv^2\right) + P_2 + Dgh_2$$

To isolate the lateral wall pressure (P) and the velocity (v), a few assumptions will be made to simplify this equation by eliminating certain factors. First, the value for height (h) does not appre-

continued on next page

ciably change because the flow through the tracheobronchial tree originates from the pressure gradient between the mouth and the alveoli. Second, gravity (g) will have a constant effect on the flow of air through the lungs. Finally, both the fluid density (D) and 1/2 are constants, and can be factored out also. Because these four factors can be eliminated from the equation, the following proportional expression results.

$$\left(v_2^2 - v_1^2\right) \propto \left(P_1 - P_2\right)$$

According to the Bernoulli equation (not discussed in detail here because of space limitations), two gradients exist at the narrowing of the funnel-shaped tube. One is the velocity squared gradient, and the other is the lateral wall pressure gradient.

As a fluid flows through a funnel-shaped conduit, like the one already described in the law of continuity discussion, the kinetic energy (1/2Dv2) increases at the narrowing as manifested by the increased velocity of the flow at that point. At the same time, the pressure energy (P) decreases as indicated by the drop in the lateral wall pressure. The transformation of pressure energy to kinetic energy at the constriction where the cross-sectional area of the conduit decreases preserves the law of conservation of energy.

The correlation between the lateral wall pressure and the velocity delineated by Bernoulli has therapeutic consequences. As air flows through partially obstructed airways under the influence of a constant driving pressure, the velocity of the flow will increase through these narrowed airways, and the lateral wall pressure will decrease. Increasing the flow will magnify the problem by widening the pre- and post-obstruction velocity gradient, and by lowering the lateral wall pressure gradient further. As lateral wall pressure decreases across the partially obstructed airways, less pressure becomes available for alveolar inflation distal to the narrowing.

The Bernoulli principle provides the theoretical basis for the use of heliox to relieve upper airway obstruction. Any gas, regardless of its density, will develop an increased velocity gradient and an increased lateral wall pressure gradient as it flows through a partial obstruction. Because a helium-oxygen mixture is less dense than an air-oxygen mixture, heliox will lessen the degree to which both the velocity and lateral wall pressure gradients change. Therefore, heliox causes the lateral wall pressure to decrease to a lesser extent, and produces less of a velocity increase across the partial obstruction. Essentially, less pressure energy is converted to kinetic energy when heliox is breathed, enabling more pressure to be available for lung inflation beyond the obstruction.

As an aside for baseball aficionados, a combination of the Bernoulli principle and the Magnus effect are responsible for causing a spinning baseball to curve. A spinning baseball has more air turbulence on top of the ball, producing slower air speed above the ball. Meanwhile, air moving under the baseball accelerates and moves faster, producing less pressure on the bottom of the ball. The ball then moves downward.

The Venturi effect incorporates the Bernoulli principle by incorporating an entrainment port at the site of the convergence of the funnel-shaped tube. The entrainment port in this location enables the influx of the flow of another fluid because the lateral wall pressure decreases at this point. The consequence of the entrainment of an additional flow is the exiting from the Venturi of a total flow greater than that entering the system. Essentially, the flow out of the system exceeds the flow in. Many oxygen therapy devices employ the Venturi effect to accomplish air entrainment for the purpose of diluting 100% oxygen (used as the source gas) with room air. The ability to dilute the source gas with these devices enables the respiratory therapist to deliver various flows and oxygen concentrations to patients experiencing a variety of clinical conditions.

To summarize, the law of continuity describes the inverse relationship between the cross-sectional area and the velocity, whereas the Bernoulli principle explains the inverse relationship between the lateral wall pressure and the velocity. Finally, a Venturi system exploits the lateral wall pressure drop through a stricture to entrain another fluid into the system.

For excellent demonstrations and information of the law of continuity, Bernoulli principle, and Venturi effect, readers are encouraged to refer to the following websites: 1) http://home.earthlink.net/~mmc1919/venturi.html, 2) http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html, and 3) http://www.ce.utexas.edu/prof/KINNAS/319LAB/Applets/Venturi/venturi.html. The third website referenced here was made available through the courtesy of Professor Spyros A, Kinnas at the University of Texas at Austin.

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