The Airways and THE LUNGS

BY DAVID MARLIN, BSC, PHD

The forgotten organs

By the time a horse crosses the finish line in a five-furlong race, has completed a Grand Prix show jumping round, or gone one-sixth of the way round a 3-star cross-country course, he will have moved somewhere around 1,800 liters of air in and out of the lungs. If you find 1,800 liters hard to visualize, then think of six bathtubs full of air. This equates to moving two five-gallon buckets of air into and out of the lung every second.

The air inhaled during a race will consist of around 380 liters of oxygen (the rest being made up of the gas nitrogen). The horse will take up into the blood and use around a quarter of this oxygen, i.e., 95 liters.

Of the total amount of energy the racehorse needs to get from the starting gate to the finish in the five-furlong race, around 70% will come from aerobic (oxygen-based) metabolism. The same can be said for the show jumping horse (70%) and a horse completing the cross-country portion of a three-day event (90%).

Aerobic metabolism is essentially the process of using oxygen to get energy from glucose (carbohydrate) in structures inside the muscle cells known as mitochondria. The remainder of the energy comes from anaerobic metabolism, which also breaks

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down glucose to generate energy. The anaerobic process can work whether oxygen is present or not.

The main difference here is the anaerobic system is very fast, but inefficient, and it can be used for only a short period of time due to the build up of lactic acid. Aerobic metabolism is not so fast, but it is very efficient at generating the energy to run.

So, even in a race or jumping round lasting less than a minute, the majority of the energy generated by the muscles must come from using oxygen to "burn" carbohydrates. Even in a Quarter Horse race (involving short, intense bursts of speed), around 40% of the energy to run comes from aerobic metabolism.

These examples underline the importance of a respiratory system. The harder a horse works, the more oxygen it needs and the more air it must move into and out of the lungs. In fact, these are so tightly coupled that if a horse doubles its speed, it will need to double the amount of air moved into and out of the lungs.

Fuels for Exercise

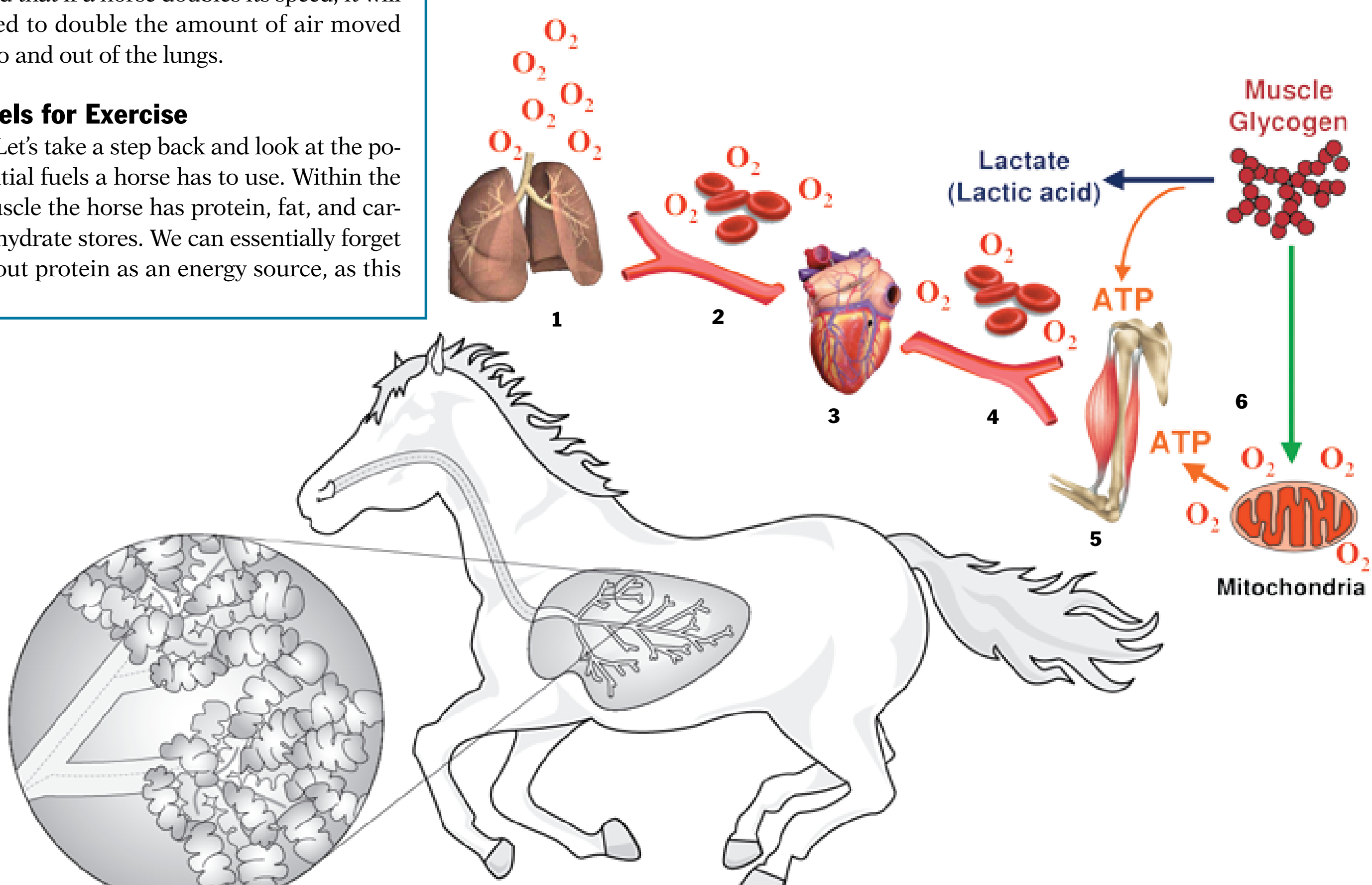
Let's take a step back and look at the potential fuels a horse has to use. Within the muscle the horse has protein, fat, and carbohydrate stores. We can essentially forget about protein as an energy source, as this is only used in extreme situations (e.g., during starvation). Fat becomes an important energy source during low- to moderate-intensity prolonged periods of exercise (e.g., endurance riding). The breakdown of fat to yield energy cannot take place without a constant supply of oxygen—in much the same way as the wax around a candle will not burn without oxygen.

For almost all other sports and for anything more than a slow canter, the horse relies primarily on carbohydrate stores within the muscle cells. These carbohydrates are stored in the form of lots of glucose molecules linked in chains known as glycogen—the animal equivalent of starch in plants.

There are two ways to break down the glycogen to yield energy. The first is without oxygen (anaerobic), which results in the end product lactic acid. The anaerobic system is a very quick way to get energy and does not require oxygen, but it has a self-limiting mechanism built in that stops the horse from running at maximum for long periods and damaging its body. Lactic acid production is essential for acceleration and high-speed running, but it is inefficient for slower speeds over longer distances. You can think of lactic acid as a big fan sucking the glycogen through the series of reactions. So, Nature has provided a more efficient way of getting energy from glycogen, and this is where aerobic metabolism comes in.

With the aerobic cascade, the mitochondria can break down the glycogen in the muscle and liberate its stored energy. The aerobic system produces around 20 times more energy from the metabolism (breakdown) of glycogen compared with the anaerobic metabolism to lactic acid. The aerobic process is not as fast, but it is much more efficient, and this form of energy generation can be used for minutes to hours of exercise.

The pathway for transporting oxygen from outside the horse down to the mitochondria inside cells



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The respiratory system moves air containing oxygen (O_2) from outside the body into the lungs (1). Once transferred to the bloodstream at the level of the capillaries and alveoli of the lungs (inset of horse illustration), the oxygen binds to the hemoglobin of red blood cells (2). The oxygen is pumped by the heart (3) around the body (4), and at the muscle (5) the oxygen leaves the red blood cells and crosses into the muscle cells, where it diffuses into the mitochondria (6). Here, it allows the mitochondria to break down glycogen in the muscle and generate energy (ATP).

AIRWAYS & LUNGS

The Respiratory System's Main Function

So where does the respiratory system fit in? We have already said that mitochondria need a steady supply of oxygen to release the potential energy stored in fuels in the muscle, such as fat and glycogen. The problem is that almost all mitochondria in muscle cells are a long way from any oxygen. True, the skin is not entirely impermeable and some oxygen could diffuse in (move from areas of high concentration, i.e., outside the body, to low concentration, i.e., inside the body) across the skin, but this is a very slow process and cannot sustain resting oxygen requirements, let alone those during exercise, which can be up to 70 times higher than at rest. If you are small enough an organism (such as a bacterium) this is an option. For an animal the size of a horse, we need a different solution. This is where the respiratory system and the cardiovascular system (heart and blood vessels) come in.

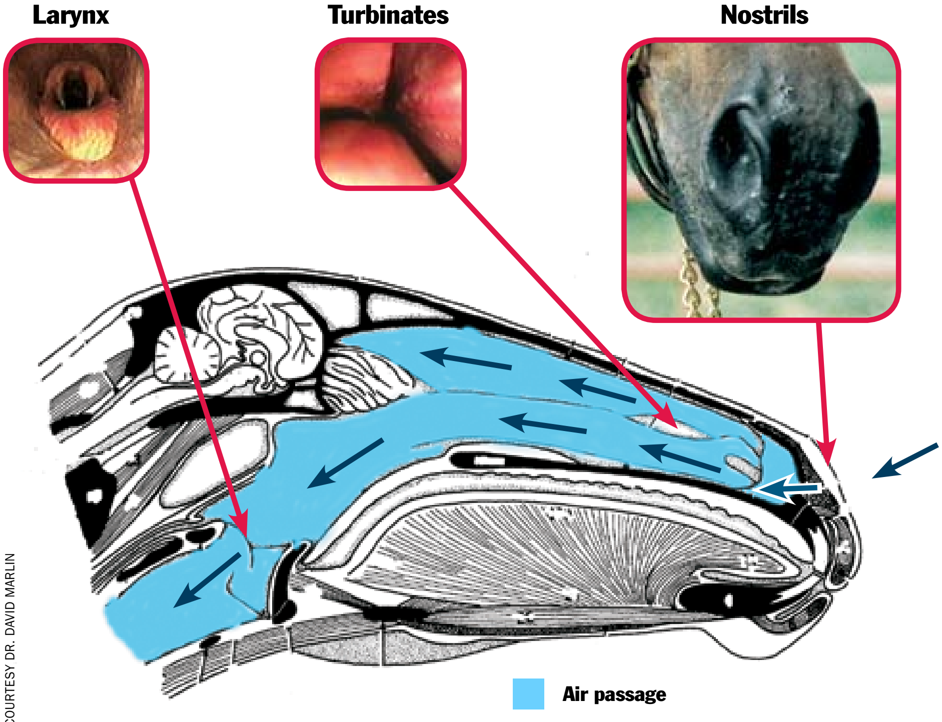
The respiratory system moves air containing oxygen from outside the body to inside the lungs, bringing the oxygen as close as possible to the blood in the circulation. In fact, when the blood and the air are closest they are only separated by a distance of 1⁄100th the width of a human hair. At this stage the transfer of oxygen from the airway (tubes containing air) across this thin membrane into the blood takes place by the process of diffusion, i.e., the oxygen moves from the highly concentrated air to the lesser-concentrated blood.

Once in the bloodstream the oxygen is bound to hemoglobin (the molecule inside red blood cells that makes blood red), and then the oxygen-rich blood is pumped around the body by the heart.

At the muscle the reverse process takes place, with oxygen leaving the red blood cells and crossing into the muscle cells, again by diffusion, because the oxygen level in the blood is higher than in the muscle cells. A final step of diffusion takes place within the muscle cells as the oxygen moves to the areas within the cell where the oxygen content is even lower—inside the mitochondria.

So by the time it gets inside the mitochondria, the oxygen concentration might only be around 1⁄80th of what it is outside the horse.

You might already be picking up that this is a potentially very important limiting step for a horse's ability to exercise. In fact, it is documented that some of the best racehorses (especially those racing over middle and longer distances) have large hearts and/or a high capacity to use oxygen—something referred to as maximal oxygen uptake or aerobic capacity. So the primary function of the respiratory system is to bring oxygen in air down into the lungs, where it can pass across a thin membrane into the blood and then be pumped around the body.



The horse does not breathe through its mouth and nose like we do. The horse only breathes through its nostrils. The nasal passages in the horse are separated from the oral (mouth) cavity. They only breathe through their mouths if they have an injury or abnormality to the soft palate (the structure that separates the mouth from the nasal passages).

Other Respiratory System Functions

One of the other important functions of the respiratory system is to get rid of carbon dioxide, a waste product produced within the mitochondria. This is effectively the same as the process for bringing oxygen in, but in reverse. Carbon dioxide moves out of the cells by diffusion, as the concentration of carbon dioxide inside the cells is higher than in the bloodstream. When the blood reaches the lungs, the carbon dioxide diffuses out across the membrane and into the airways because the concentration of carbon dioxide in the airways is lower than in the blood. The carbon dioxide is then exhaled. Accumulation of carbon dioxide is undesirable and can contribute to the development of fatigue during exercise, so it's important that as much as possible is exhaled as fast as possible.

The lung is also an important filter. All the blood in circulation passes through the lungs when it comes back in veins from being pumped out around the body in arteries. As such, the lung is ideally placed to filter out any small blood clots (thrombi) or gas bubbles (emboli). It might not be great to have a pulmonary embolism (a gas bubble in the lung), but it's still highly preferable to having it lodge in a coronary (heart) vessel or the brain, as the lung has a better capacity to deal with bubbles and clots than most other organs in the body.

The lung is also able to activate or deactivate certain hormones in the circulation, and in some cases the lung acts as an endocrine organ, actually releasing hormones which can have effects on the whole body.

The skin, the lung, and the gastrointestinal tract are the body's interfaces with the outside world. The lung, therefore, has a highly developed immune system different to that in other parts of the body with specialized types of white blood cells to deal with things that could be inhaled, such as particles, bacteria, fungi, and viruses.

Finally, perhaps one of the most important, but often overlooked nonrespiratory (i.e., not related to moving gases in and out) functions of the respiratory system is the control of body temperature (thermoregulation). If a horse is taken from a cool climate to a warmer climate, say, to a temperature of around 85°F (29.44°C), then one of the first things that can be noticed is an increase in the rate of breathing at rest. While the horse will additionally open up small blood vessels in the skin in an attempt to lose heat and might sweat slightly, respiratory heat loss is also an important thermoregulatory mechanism for the horse.

In fact, we can take an opportunity here to dispel a common horsemen's myth. When horses blow after hard exercise, it has commonly been believed that this is because they are trying to get more oxygen into the blood.

From studies on treadmills where we can measure the blood oxygen levels during and after exercise, we know that whilst the blood oxygen level might fall during intense exercise, even as the horse is pulling up, the levels return to and, in fact, go above the normal resting level. The main thing that controls blowing after exercise in horses is how hot they are, not the blood oxygen level.

A Unique System

To some extent the horse is still an enigma. There is no other animal that can carry the weight of a person (often representing an extra 10-15% of its own body weight) and move at speeds of 35 mph or more. It might, therefore, not be surprising that the horse's respiratory system displays some curiosities, especially when compared to ourselves.

10 Things you might not know about the horse's respiratory system

1) The horse does not breathe through its mouth and nose like we do. The horse only breathes through its nostrils. The nasal passages in the horse are separated from the oral (mouth) cavity. They do not breathe through their mouths unless they have an injury or abnormality to the soft palate (the structure that separates the mouth from the nasal passages).

2) At canter and gallop normal horses take one breath perfectly in time with one stride. This is referred to as respiratory-locomotor coupling. A normal horse might swallow one or two times during each minute of exercise, but no more. The amount of time taken to inhale is the same as the time taken to exhale.

3) The amount of air moved in and out of the lungs increases in direct proportion to how fast the horse is running. If a horse runs twice as fast, it must move twice as

much air in and out.

4) When horses inhale during exercise, around 90% of the resistance (obstruction) to air movement is in the airways that are in the head, namely, the nostrils, the nasal passages, and the larynx. But when horses are exhaling the majority of resistance to air movement (55%) is in the airways within the lung.

5) If you tighten a horse's girth too much, it will affect the horse's performance—not because of constricting the chest and preventing the lungs from expanding, but because it decreases the effectiveness of the muscles around the front of the chest and shoulder that move the forelegs.

6) Horses do not breathe by expanding and contracting their chests during the canter and gallop. They expand and contract the chest when breathing at rest, when breathing at walk and trot, and perhaps most noticeably when blowing hard after exercise. But during canter and gallop all air movement comes from movement of the diaphragm.

7) Horses hold their breath over jumps and do not breathe again until they land, starting with breathing out.

8) You cannot train the respiratory system of the horse. Plenty of books will tell you that you can. A number of scientific studies show the reverse. The amount of air moved in and out by an unfit horse at a fixed speed will be the same six months later when that horse is fully fit.

9) The pressure in the blood vessels within the horse's lungs (referred to as pulmonary blood vessels) during galloping is four to five times higher than resting pressure. This is one of the factors that puts stress on the very thin walls of the blood vessels and leads to some of them rupturing.

10) If all the airways in the lung were opened out and laid flat on the ground, they would occupy a total area equivalent to 10 tennis courts.

Limiting Factors

It should now be obvious that the respiratory system of the horse is working at its limit and can be under considerable stress. It also appears to have no capacity to respond to training, unlike muscles and the cardiovascular system, for example. But does the respiratory system limit performance? Based on a variety of different pieces of evidence, the answer is probably yes.

First, if we allow horses to breathe air with a higher-than-normal oxygen concentration (say 30%, as compared with the normal 21%), then the cardiovascular system still has spare capacity to transport the extra oxygen and the muscles have the capacity to use it. This suggests that if the lung were more efficient and able to bring in more oxygen, then the other systems could take advantage of the fact.

Second, studies that have reduced the load on the respiratory system by allowing horses to breathe 21% oxygen in a mixture where the normal nitrogen in air has been replaced by the less-dense gas helium, have shown that horses can exercise for longer, i.e., they do not fatigue as early. Again, we are reducing the strain on the respiratory system and the effect is an improvement in performance.

Third, we also know if we mechanically support the upper airways through external means (i.e., the nasal strips some competitive horses wear), horses can either move more air in and out, or move the same amount of air with less effort. This increases the amount of oxygen available to the muscles and either delays the onset of fatigue or increases the capacity for exercise.

Take-Home Message

Because of the high prevalence of lameness and the ability of owners to readily detect it themselves, this is usually the most common reason for calling out a veterinarian. In relation to poor or decreased performance, the heart can easily be examined at rest or monitored during exercise, so again, heart problems are usually readily identified during veterinary investigations. However, the respiratory system oftentimes gets forgotten.

What is the problem with the lungs? Well, you can't see them and most of the time you can't hear them either. However, this is a system working at its limit. It needs proper care and all the support you can give it.

ABOUT THE AUTHOR

David Marlin, BSc, PhD, *is an equine respiratory and exercise specialist and holds positions at universities both in the United States and in the United Kingdom. He has published more than 150 scientific papers. He is the chairman of the International Conference on Equine Exercise Physiology group. He also works in a professional capacity with riders, owners, and trainers in all equestrian sports, including racing, and is involved in the lead-up to the Beijing Olympics.*