How Well Designed Is the Human Lung?

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Although it is often stated that the structure of the human lung is ideally suited to its gas exchange function, the lung is very vulnerable under some abnormal conditions. One example is the postoperative period in a patient with an otherwise normal lung where retained secretions can rapidly cause unventilated areas or atelectasis and substantial impairment of gas exchange. Some pulmonologists may be surprised to learn that evolution has provided a very different, and arguably superior, lung design in the bird. Here, the gas exchange and ventilatory functions of the lung are separated. Gas exchange occurs in relatively rigid parabronchi, which are more robust than the delicate alveoli in the human lung, and ventilation is performed by highly expandable air sacs. A comparison of these two completely divergent evolutionary paths throws light on some of the problems of the human lung.

Suppose you were asked to design a heat exchanger, such as the radiator of a car. The purpose of this is to enable heat from the engine to be eliminated to the outside air. One way would be to pump the hot coolant fluid from the engine through a grid of many small tubes and have air passed across these by means of a fan. In fact, this is the time-honored design for car radiators. If you suggested this, Henry Ford would have been proud of you.

But you might come up with an alternative design in which the small tubes containing the coolant fluid were enclosed in a bellows that was alternately inflated and deflated so that the air in the bellows was heated and then expelled. In fact, you might even conceive of a design in which the small tubes themselves were part of the bellows. A critic might say that this alternative design was unnecessarily complicated and prone to problems, especially if the small tubes formed part of the moving bellows. But amazingly this is the design that evolution chose for the mammalian, and therefore human, lung.

The lung is a gas exchanger, which is closely analogous to a heat exchanger. Although in the latter, heat is taken from the engine and eliminated into the surrounding air, the lung does this for carbon dioxide, and at the same time it takes up oxygen.

The route taken by evolution for the mammalian lung is even more astonishing when we realize that a completely different path was pursued in designing the bird lung. Indeed, the bird has a lung rather like the classic car radiator. A comparison of

these two quite divergent evolutionary paths helps us to understand some of the vulnerabilities of the human lung.

HUMAN LUNG

At first sight, the structure of the lung seems to be well suited to its major function of gas exchange. As every first-year medical student is taught, the blood–gas barrier has a very large area and is extremely thin. These characteristics make it ideal for rapid diffusion of oxygen and carbon dioxide. In addition, the branching airway structure is very efficient, with little unevenness of ventilation and a relatively small dead space compared with the total lung volume. The same considerations apply to the blood vessels, which enable the total output of the right heart to be presented to the blood–gas barrier with little unevenness of perfusion. The compliance of the lung is large so that only small pressures are required to expand it, and surfactant promotes the stability of the alveoli. The pulmonary vascular resistance is remarkably low with the result that the work of the right heart is small. The mucociliary escalator and the alveolar macrophage system are effective in keeping the lung clean. Furthermore, the lung can handle a more than tenfold increase in oxygen consumption and carbon dioxide output during exercise. All these features reflect a remarkable evolutionary adaptation.

VULNERABILITY OF THE LUNG IN DISEASE

Although the features of the human lung listed above are certainly impressive, some shortcomings of the design became evident in mild disease. Here, I am not referring to florid pathologic conditions, such as emphysema, severe asthma, interstitial lung disease, or acute respiratory failure, where of course it is not surprising that the function of the lung is greatly impaired. Instead, I am pointing to relatively minor conditions in an otherwise normal lung, such as retained secretions or aspiration in an obtunded patient or one in the postoperative state. In these situations, occlusion of an airway can rapidly lead to reduced ventilation or atelectasis and substantial impairment of gas exchange.

The root cause of these problems is that the delicate alveolar tissue is responsible for both ventilation and gas exchange. The diaphanous alveolar walls contain the capillaries with their extremely thin blood–gas barriers, and the same structure is responsible for the volume changes that move air into the lung. It is this combination of functions that makes the mammalian lung so vulnerable. By contrast, inhalation of aspirated material in the bird lung will presumably end up in the capacious air sacs and not interfere with the function of the gas-exchanging tissue.

AN ALTERNATIVE DESIGN

Some pulmonologists may be surprised to learn that many millions of years ago, evolution also took a completely different path and arguably ended up with a better design for a lung than in mammals. This is seen today in birds. It is pertinent to point

(Received in original form October 28, 2005; accepted in final form December 27, 2005)

*The word “design” in the title and elsewhere in relation to the lung is shorthand for the result of evolutionary changes.

Supported by National Institutes of Health grant RO1 HL60968.

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Am J Respir Crit Care Med Vol 173, pp 583–584, 2006

Originally Published in Press as DOI: 10.1164/rccm.200510-1682OE on December 30, 2005
Internet address: www.atsjournals.org

out that only two groups of vertebrates have been successful in achieving very high levels of exercise. These are mammals and birds, and the highest maximal oxygen consumptions in relation to body weight are seen in birds. Flying is a very energetic activity and requires very efficient lungs.

The two evolutionary paths diverged from the ancestors of present-day reptiles (Figure 1). One line of evolution led to the bronchoalveolar lung of the mammals, whereas the other produced the air sac/parabronchial structure of the bird. Interestingly, intimations of this separation can be seen in present-day reptiles. For example turtles, monitor lizards, and crocodiles have a lung structure somewhat similar to the alveolar lung, although the "alveolar" compartments are larger. On the other hand, snakes typically have a lung with a vascularized cephalad region that performs the gas exchange while the caudal but nonvascularized saccular area is responsible for the ventilation.

The essence of the bird lung is that ventilation is brought about by using nonvascularized air sacs that are very expandable. The inspired air is drawn into an air sac and subsequently pumped through the parabronchial region, which is essentially rigid. This gas exchanger is composed of blood capillaries like those in the mammalian lung but instead of these being surrounded by large alveolar spaces, the capillaries are immediately adjacent to very small air capillaries that are only 3 to 15 μm in diameter. Aerodynamic valving ensures that the gas only passes in one direction through the parabronchi (1). This is a somewhat simplified description of the bird lung; for example, there are several air sacs and some birds have two sets of parabronchi. In addition, the bird lung has a "cross-current" gas-exchanging system, which is believed to be more efficient than that in the human lung.

The resulting differences between the mammalian and bird designs are striking. In the bronchoalveolar lung, the inspired gas

is drawn into blindly ending acini and alveoli, and the terminal airspaces need to have a sufficiently large cross-sectional area for diffusion of the inspired gas to reach the alveolar walls where the capillaries are located. This is one reason why the alveoli in the human lung are much larger than the air capillaries in the bird lung; human lung alveoli are approximately 0.3 mm in diameter. Furthermore, the alveolar walls must be very thin so that they can change shape to allow gas to enter them on inspiration. The result is that the capillaries are strung out along delicate alveolar walls. This complex structure is a direct consequence of the reciprocating nature of ventilation.

The structure of the parabronchial lung is entirely different. Here, gas flow is unidirectional along the parabronchi, the reliance on gas diffusion to reach the blood capillaries is much less, and there is no necessity for the relatively large alveolar spaces of the mammalian lung. The air capillaries and the blood capillaries have approximately the same dimensions. The structure of the parabronchial tissue is therefore much more robust and rigid.

Evidence for the rigidity of the parabronchial tissue comes from experiments where the pressure around the parabronchi, or the pressure in the capillaries is altered. For example, when the pressure outside the parabronchi is raised in ducks, there is very little impairment of gas exchange, indicating that the air capillaries are remarkably resistant to collapse (2). This behavior is very different from that seen in the mammalian lung where compression of the parenchyma rapidly results in impaired gas exchange as a result of the collapsed and unventilated alveoli. Again, the bird lung behaves very differently if the capillary pressure is raised. In experiments in ducks where the pulmonary artery to one lung is occluded, there is very little change in the vascular resistance of the unoccluded lung (3). This is a completely different result from that seen in the mammalian lung where occlusion of one pulmonary artery results in a dramatic fall in vascular resistance in the unoccluded lung as a result of distension and recruitment of capillaries. Both of these experiments emphasize the robust rigid nature of the parabronchial tissue.

CONCLUSIONS

Although the structure of the human lung appears to be well suited to its primary function of gas exchange, the lung is very vulnerable to minor insults, such as retained secretions. This vulnerability stems from the fact that the delicate alveolar tissue is responsible for both ventilation and gas exchange. Evolution found a better arrangement in the bird where the ventilation and gas exchange functions are separate. Of course, the apparently better design of the bird lung is largely of academic interest to a pulmonologist because there is no way of exploiting these properties in the mammalian lung. Nevertheless, this alternate path of evolution demonstrates some of the vulnerabilities of the human lung and is interesting on this account.

Conflict of Interest Statement: J.B.W. does not have a financial relationship with a commercial entity that has an interest in the subject of this manuscript.

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Figure 1. Two evolutionary paths for the development of the lung. In the bronchoalveolar lung of humans, both the ventilation and gas exchange functions are performed by the delicate, vulnerable alveolar tissue. In the bird lung, the ventilation and gas exchange functions are separated. Ventilation is the responsibility of highly expandable air sacs, whereas gas exchange occurs in robust, rigid parabronchial tissue.