Inspirational Evolution: the Avian Lower Respiratory Tract

Sue Jaensch
smjaensch@yahoo.com.au

About 300 million years ago, the ancestors of the modern reptiles emerged from the water and became committed to air breathing. From these evolved the cynodonts, carnivorous reptiles believed to be the ancestors of mammals, and therapod dinosaurs from which birds descended. Although many organ systems in mammals and birds exhibit similar anatomy and physiology, the respiratory systems are radically different. The bird lung is considered to be the most efficient gas exchange mechanism of all air breathing vertebrates, topped only by the highly efficient gills of some fish.

In contrast to mammals, the avian respiratory system separates the functions of respiration and gas exchange. This has allowed a number of refinements to the lung resulting in a reduced lung volume, high gas exchange efficiency and a highly robust lung structure. Compared to an equivalent sized mammal, the average bird has a lung volume which is 20% smaller, a gas exchange area 15% greater and a blood gas barrier 60% thinner.

Table 1: Comparison of some features of the mammalian and avian respiratory tracts

		Mammalian	Avian
	Vocalisation site	**Larynx**	**Syrinx**
Trachea and bronchi	Width	Narrower	Wider
	Length	Shorter	Longer
	Dead space	Larger	Smaller
Ventilation	Gas flow	Reciprocating	Unidirectional
	Mode of pulmonary flow	Convection and diffusion	Convection
	Stratification of inhaled gas	Yes	No
	Separation of ventilation and gas exchange functions	No	Yes
Gas exchange tissue	Parenchyma	Deformable	Rigid
	Thickness of blood gas barrier	0.6-0.7 µm	0.1-0.5µm
	Diameter of gas exchange system	300µm	5µm
Gas exchange	Cross current exchange	No	Yes

Respiratory cycle

Gas flow directions in the avian respiratory tract has been the subject of many studies published over the last 40+ years, and the theories of gas movement have changed dramatically over this time. Some of the early models declared that there was no gas flow through the lungs at all! Under the currently accepted model, it takes two respiratory cycles to move gas through the entire respiratory tract. This initially appears inefficient, but in fact is an important physiological process behind respiratory efficiency in birds, as it allows continuous and unidirectional gas flow through the lung both on inspiration and expiration. Control of the direction of airflow though the respiratory tract remains poorly understood, with physical valving, speed of gas flow and arteria P_{CO2} all likely playing a role. CO_2 receptors are the principle driving force behind respiration in birds. These are directly inhibited by halothane, explaining the ready induction of apnoea when using this anaesthetic agent.

We are all familiar with diagrams depicting gas flow though the respiratory tract (Figure 1). In reality, gas flow is more complex, with approximately 50% of the inspired air passing into the lungs and 50% into the caudal air sacs. The inspired air that directly enters the lungs moves though both neobronchi (in species in which they is present) and parabronchi, and contributes significantly to gas exchange. On the first expiration, the gas from the caudal air sacs passes into the lungs. On the second expiration, the gases move from the lungs into the cranial airs sacs. On the second expiration, these gases are finally exhaled.

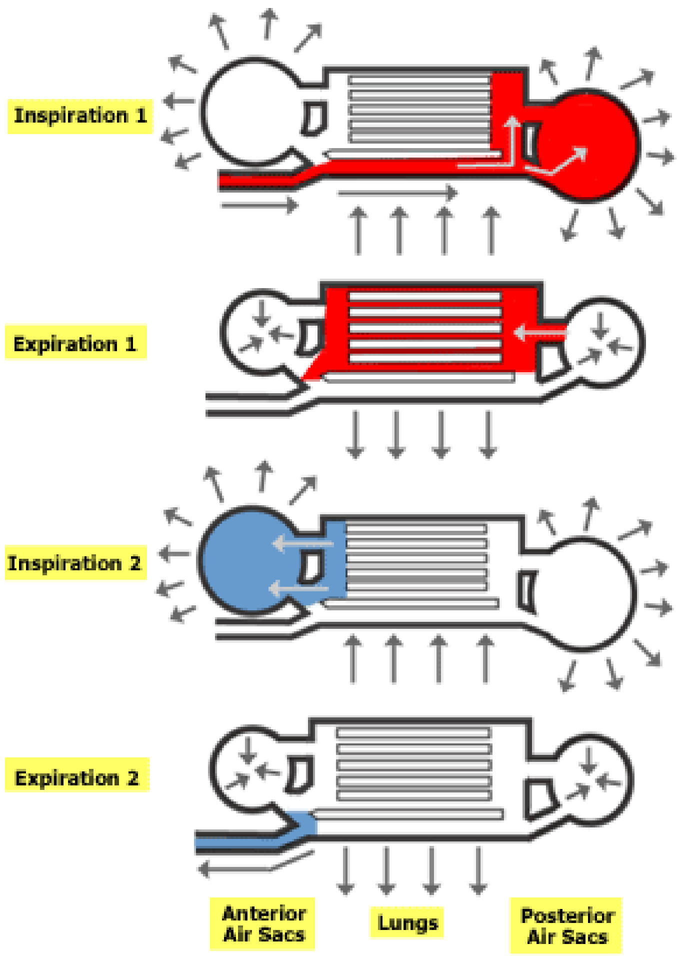


Figure 1: Avian respiratory cycle

http://www.peteducation.com/article.cfm?c=15+1829&aid=2721

Gas in the caudal air sac has a very slightly lower P_{O2} and slightly higher P_{CO2} than room air largely due to dead space of the trachea plus some minor gas exchange as some inspired air passes through the lungs on the way to the caudal air sacs. Gas in the cranial air sacs has a P_{O2} significantly lower and P_{CO2} significantly higher than room air (see Table 2).

Trachea

Inhaled air passes down the trachea, through the syrinx, then down the bronchi. This seems like a simple enough process, but marked species variation in anatomy of the trachea and syrinx are present. Some species have remarkably elongated and convoluted tracheas (Figure 2). These are thought to have evolved to allow loud and resonate vocalisation, and are variably theorised to allow a trombone like effect or a harmonic vibrating effect (in species with tracheas within the keel). However, not all species with such trachea make loud vocalisations, and some birds produce similarly loud and resonant vocalisations without an elongated trachea.

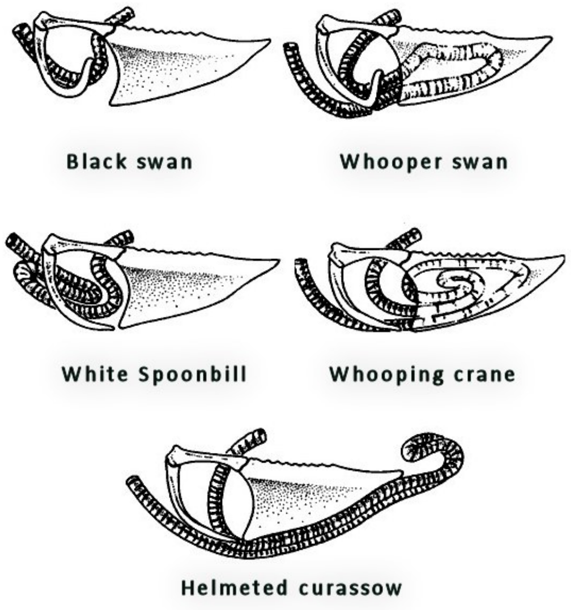
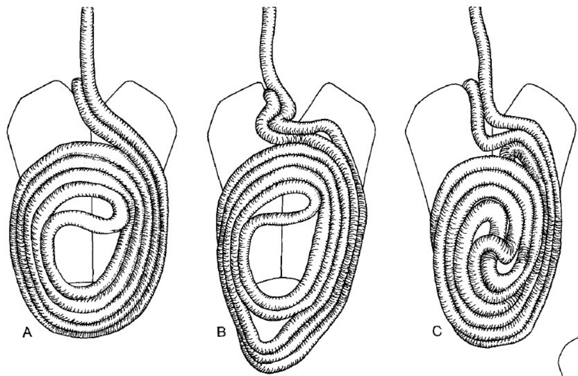


Figure 2a. Examples of tracheal loops



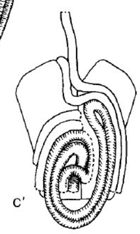


Figure 2b. Elongated tracheae of the trumpet manucode (*Phonygammus keraudrenii*), family Paradisaeidae.

Three whole adult males, American Museum of Natural History Alcohol Collection nos. 17, 19 and 18. Specimen 18 (C,C') was at least 13 years old when it died - its trachea was overlapped in two places, and was approximately 75 cm long.

Figure 2: **Variations in avian tracheal anatomy**

Both images: **http://scienceblogs.com/tetrapodzoology/2009/04/29/elongate-avian-trachea/**

From a medical point of view, these convoluted tracheas may reflect in an increased risk of foreign body deposition, an increased risk of spread of respiratory disease to surrounding structures, and due to their dead space, potential complications with anaesthesia. Radiology and endoscopy can be used to evalate tracheal disease. Endoscopy may allow foreign body removal and biopsy of lesions for histology and culture. Laser ablation and baloon dilatation of tracheal obstructions are described in the literature. Surgical excision of tracheal lesions may be complicated by the complete cartilagenous rings, minimal ability to elongate the trachea to achieve closure and rapid reduction in diameter of the tracheal below the larynx in some species, resulting in mis-match of sizes when anastomising.

Syrinx

The syrinx is located at the end of the trachea and is variably fused to tracheal and / or bronchial cartilages. There is considerable variation in the anatomy of the syrinx between species, with some birds having extensive out-pouching structures which may be asymmetrical (left Figure 3). The syrinx undergoes significant alternations in internal structure during vocalisation with rapid contraction of the syringeal muscles either unilaterally or bilaterally (right Figure 3).

The convoluted structure of the syrinx provides the first major site of change of air flow speed and direction within the respiratory tract. Thus it is a common site for deposition of inhaled particles. As a result, obstruction by foreign bodies or granulomas is relatively common. The syrinx can also be affected by nutritional deficiency resulting in squamous metaplasia, parasites and neoplastic obstruction.

The location of the syrinx complicates therapy. Similar disease entities occurring in a mammal, although problematic, are more amenable to surgical evaluation and treatment. Endoscopy can be used to evaluate disease in the syrinx, and may be curative when an inhaled foreign body or inspissated mucous plugs can be removed. Endoscopically sourced biopsy of granulomas or masses can provide diagnostic samples for histology and culture.

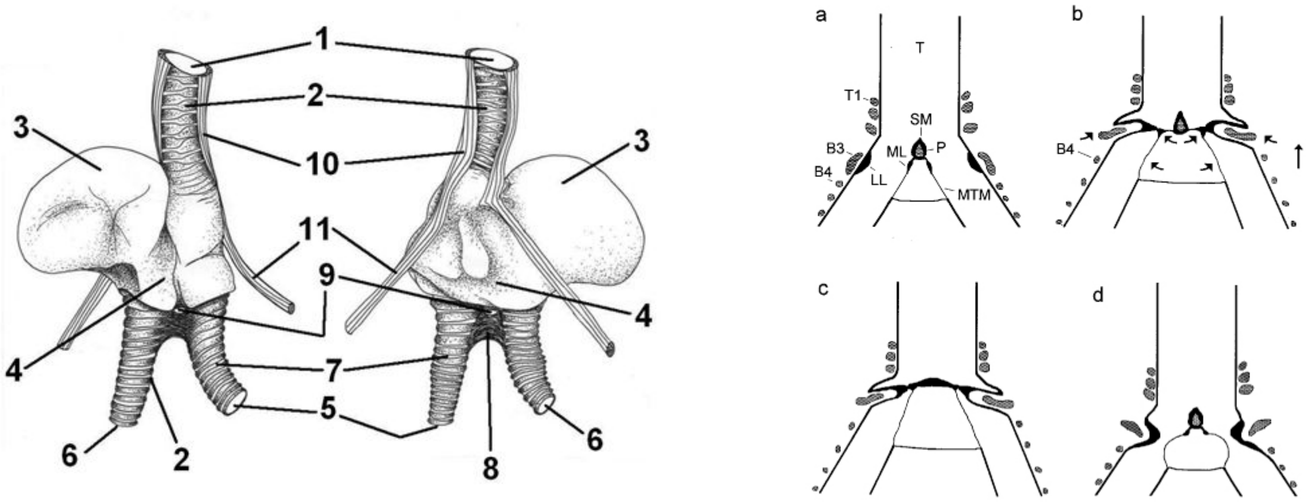


Figure 3: Syrinx functional anatomy

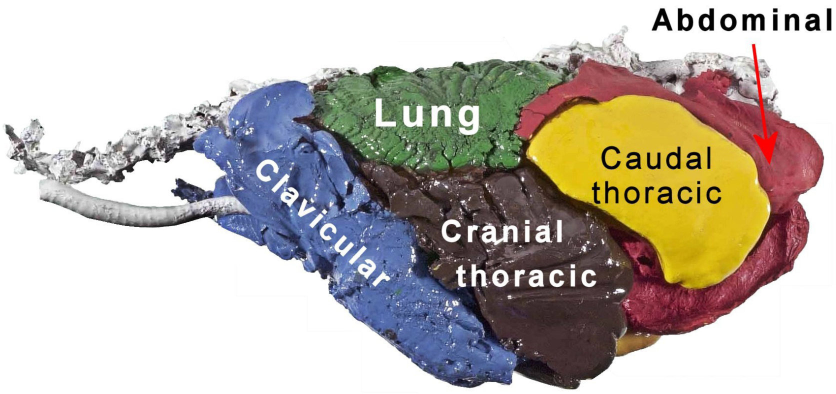
Left: **http://www.ejpau.media.pl/volume13/issue4/art-22.html**
Right: **http://www.pnas.org/content/94/26/14787/F2.expansion.html**

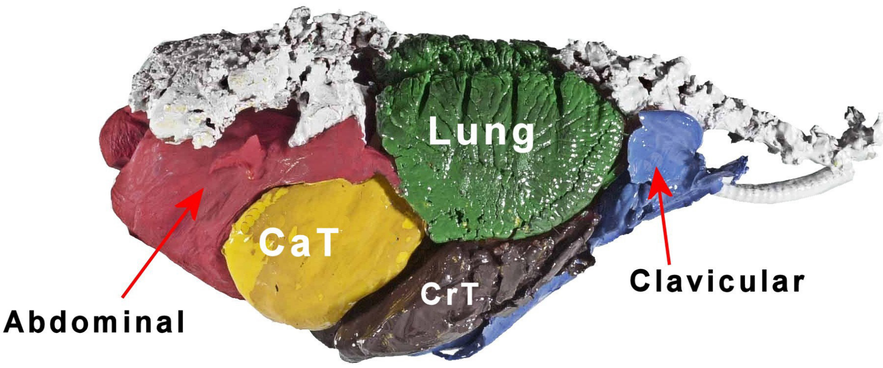
Air sacs

The air sacs are capacious, transparent structures which communicate with the lungs via the ostia. The air sacs contribute significantly to the higher respiratory volume of birds (100-200 ml/kg bw) compared to mammals (35-70 ml/kg bw). Air sacs are avascular and play no direct role in gas exchange. Their interconnections, extensions and sizes vary between species, however a common pattern in domestic species is paired cranial thoracic, caudal thoracic and abdominal air sacs, with single (or fused paired) cervical and clavicular air sacs (Figures 4 and 5). Extensions into and around bones as well as into perirenal and subcutaneous spaces are common in flying birds and less common in walking and diving birds, leading to a hypothesis that pneumaticity likely contributes to reduction in tissue mass and density. There is also a cervicocephalic air sac which arises from the infraorbital sinuses but is not attached to the lungs. This is variably developed between species, being most prominent in strongly flying birds.

The air sac walls predominantly consist of simple squamous epithelium but near the ostia patches of ciliated columnar cells occur. Diving species may have slightly thicker walled air sacs with columnar type epithelial cells. In the absence of a diaphragm, air movement through the air sacs is driven by movement of the ribs and sternum. In running or flying birds, the respiratory cycle is coupled to the wing beat or foot movements that increase thoracic volume during respiration. The uncinate processes on the ribs are important in cranially rotating the ribs (and hence ventrally rotating the sternum) during inspiration, and are particularly active when birds are resting in a sternal position. Minor tail movements can be seen with inspiration in normal birds. Exaggerated tail bobbing is often identified in birds with significant lower respiratory disease and reflects increased respiratory effort. Tail bobbing may also be identified in birds in sternal recumbency reflecting reduced mobility of the sternum in this position.

The air sacs are particularly helpful to veterinarians by providing contrast during radiography and allowing excellent visualisation of internal organs during endoscopy. They also allow for an alternative route of gaseous anaesthesia administration in cases where tracheal administration is inconvenient or impossible (see discussion below).


Abdominal
Lung
Caudal thoracic
Clavicular
Cranial thoracic


Lung
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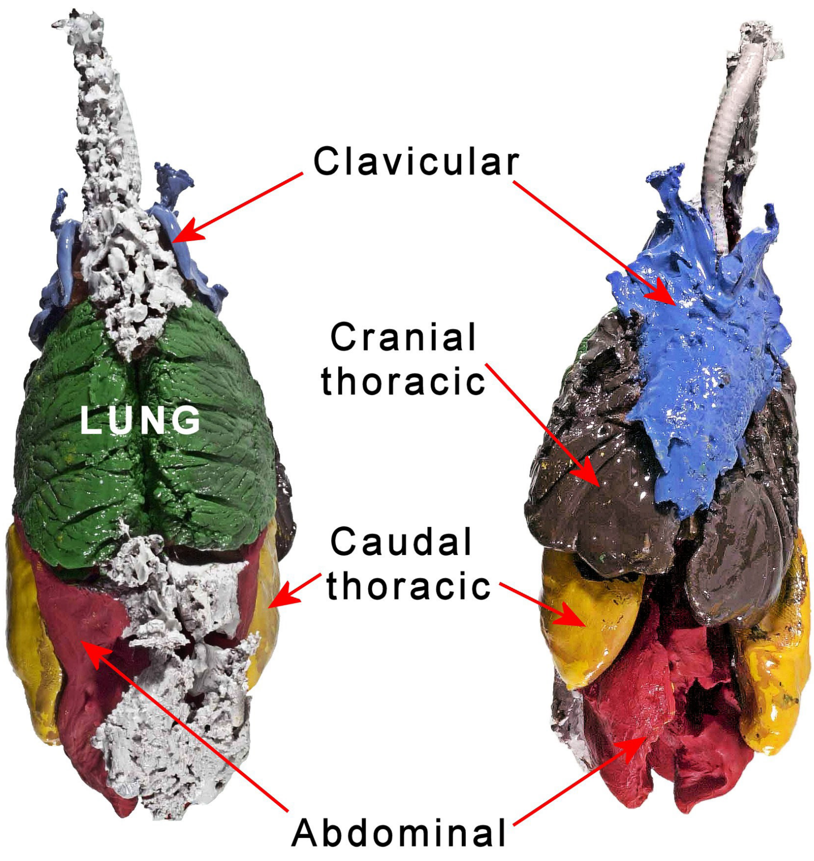
Clavicular
LUNG
Cranial thoracic
Caudal thoracic
Abdominal

The air sacs most commonly come to veterinary attention when infectious agents take root or with rupture of the air sacs causing subcutaneous emphysema. Clinical signs of air sac disease may include altered respiratory pattern (tail bobbing etc) or feather picking over areas of air sac disease. Localised lesions which do not disrupt air flow may be clinically occult. Infectious lesions are most commonly identified in the caudal air sacs, reflecting the pathway of air flow through the respiratory system. Mass lesions in the air sacs may be identified on radiography. Diagnostic samples are best retrieved via endoscopy. Options include cytology and culture using cytology brushes or lavage to collect samples, or biopsy of lesions for histology and culture. Foreign bodies can be removed by endoscopy.

As normal air sacs are poorly vascularised, systemic therapy may not result in adequate drug concentrations in the air sacs. With inflammation, vascularisation of the lesion may increase the delivery of therapeutic drugs. Nebulisation (but not vaporisation) can also be used to deliver drugs to the air sacs. Particle size is important and should ideally be no larger than 0.5 micron, but particles up to 3 micron may make it to the air sacs. Particles larger than this will be deposited in the upper airway and trachea. Nebulisation can only be expected to result in therapeutic levels of drugs in the caudal air sacs and lungs. Cranial air sacs cannot be reliably treated by this route. Systemic uptake of drugs from the air sacs is minimal.

Lungs

Advantages of the unidirectional gas flow in the lung of birds:

1. **Even ventilation of the gas exchange tissue:** In mammals, the lung remains partially inflated at the end of expiration, thus the inspiratory volume does not match the lung volume. As a result, proximal alveoli are preferentially ventilated by the inspired air. More peripheral alveoli may only receive ventilation by diffusion, which is slow and inefficient. The unilateral air flow in birds results in minimal stratification of inspired air, instead all air capillaries are evenly ventilated by convection.
2. **Higher oxygen tension of alveolar gas:** A flow on effect of the mixing of fresh and existing gas in the mammalian lung is that alveolar P_{O2} is considerably lower than the inspired air. The flow through system in bird lungs minimises stratification and allows higher air capillary and arterial oxygen tension (Table 2).
3. **Cross-current gas exchange:** Cross current gas exchange allows a highly efficient exchange of gases between the air and blood in the lungs. As blood travels towards the parabronchial lumen and air from the parabronchial lumen, there is continuous exchange of oxygen to the blood and carbon dioxide from the blood. The oxygen concentration of the blood is lower than the oxygen concentration of the air along the full length of contact. As a result, unlike in mammals, arterial P_{O2} can be higher than expired air P_{O2}.

	Mammal		Bird	
	P_{02}	P_{CO2}	P_{O2}	P_{CO2}
Inspired air	150	0	150	0
Caudal air sac			120	20
Alveoli /Air capillary	100	40	120	20
Cranial air sac			90	40
Arterial	75-90	35-45	90-100	25-30

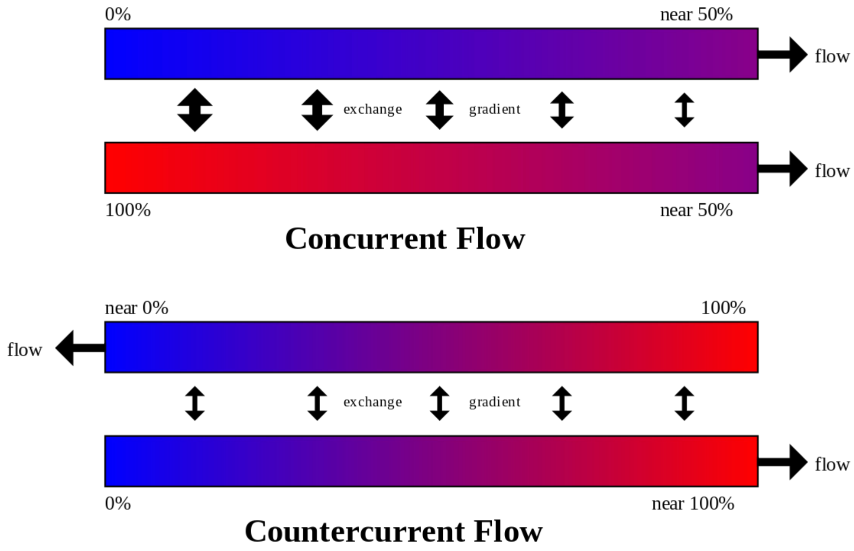

Figure 5: Comparison of concurrent flow and counter current flow

https://en.wikipedia.org/wiki/Countercurrent_exchange

4. **Small terminal air exchange units:** In mammals, air flow to the peripheral alveolar requires a mix of convection and diffusion, resulting in a need for low resistance and hence large volume alveoli. The larger diameter alveoli in mammals requires greater support (including collagen) and reduces the integrity of the alveoli walls under stress. Small diameter air capillaries allow evenly thin walled, and hence high efficiency gas diffusion surfaces with minimal support structures.

Advantages of separation of gas exchange and ventilation functions:

1. **Lack of repetitive distortion of the air exchange tissue:** In mammals, there in inherent tension between the drive for thin and efficient gas exchange surfaces, and the need for these surfaces to be robust enough to withstand repetitive distortion with every breath. In humans, this repetitive distortion is thought to result in the "normal" degree of emphysema identified in normal aging lungs. This requirement to tolerate distortion has resulted in a need for thicker walls in alveoli compared to air capillaries, and the presence of fibroblasts and collagen in the alveolar walls. As discussed above, both factors reduce efficacy of gas exchange in comparison to birds.
2. **Robust lungs**: Mammalian lung tissue is deformable. Compression of the parenchyma results in cessation of ventilation. In contrast, avian lungs are minimally deformable, with studies in penguins showing minimal change in lung volume regardless of the positioning of recumbency (note however that air sac volumes can be significantly reduced by different positions of recumbency). This robust nature has been characterised for both the air capillaries and blood capillaries in birds. In birds, pulmonary blood capillaries are supported by a three dimensional honeycomb of air capillaries providing rigidity. In contrast, mammalian pulmonary blood capillaries have little support at right angles to their axis, increasing their risk of damage. The sequella of this is an increased risk of pulmonary haemorrhage with exercise - a common outcome in racing thoroughbreds and elite human athletes.

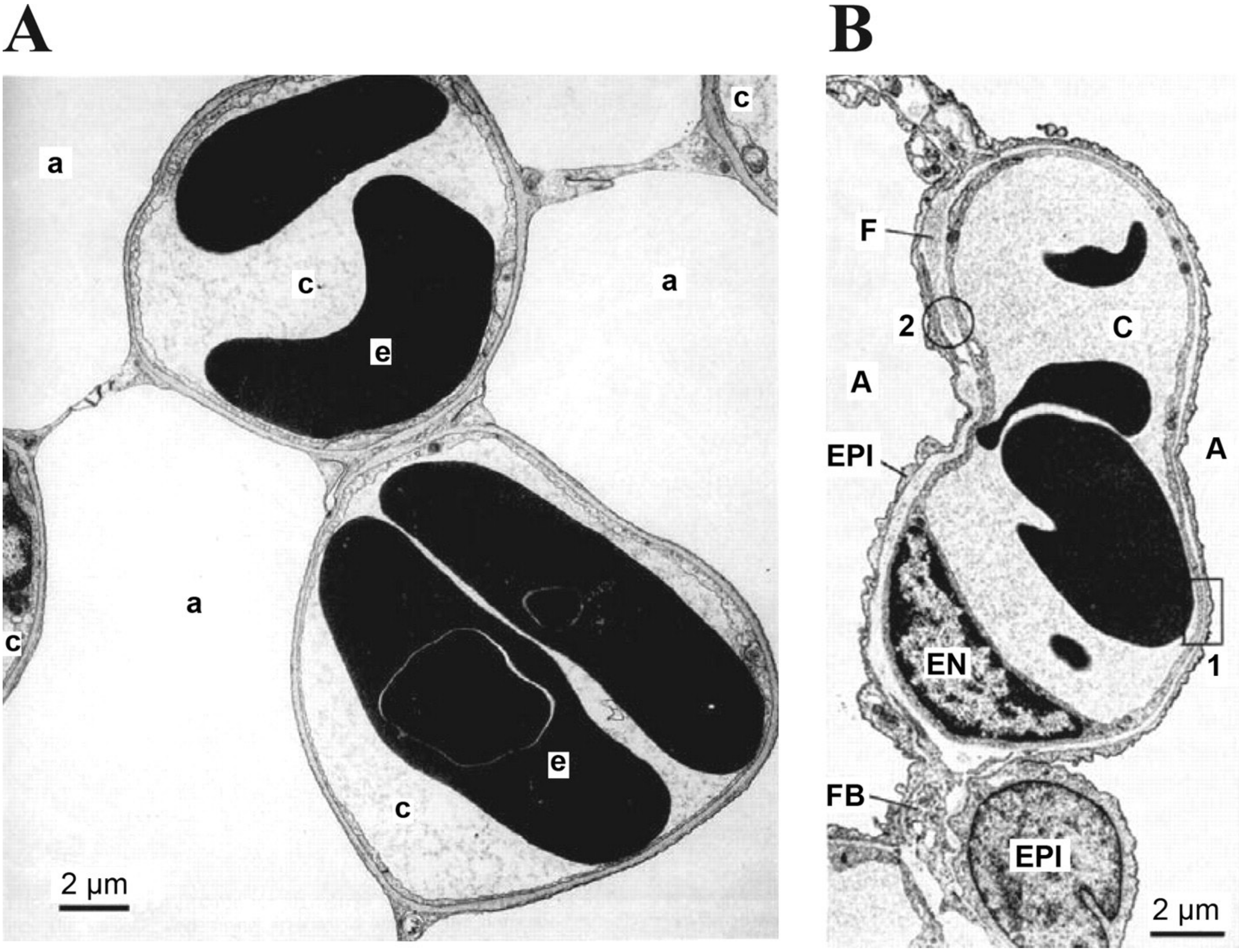

Figure 6: Electron micrographs of pulmonary capillaries in chicken (A) and dog lung (B). Note that the blood-gas barrier in the bird is much thinner and much more uniform in thickness than in the mammal. EPI, epithelium; F, fibrils of type I collagen; FB, fibroblasts.

http://ajpregu.physiology.org/content/297/6/R1625

Disease susceptibility

Respiratory disease is a relatively common clinical presentation in birds. One histopathological survey of chickens reported 10% of cases were respiratory (excluding poultry viral respiratory diseases).

The local immunity of the avian respiratory system remains relatively poorly understood. Substantial populations of lymphocytes are present in the nasal mucosa and bronchus. The trachea is lined by ciliated epithelial cells, with good efficacy in clearing inhaled small particles by mucociliary transport. Coughing occurs in birds, but has reduced clearing of mucous from the upper airways in comparison to mammals. Birds have complete cartilaginous rings in the trachea. The lack of partial collapse of the trachea during coughing in birds reduces the velocity of air flow up the trachea in comparison to mammals, and reduces the efficacy of tracheal clearing.

In the air sacs, there are small islands of lymphoid tissue and ciliated cells predominantly near the openings to the lungs, but function of these is poorly understood. There are few resident macrophages or lymphocytes in the air sacs, making them appear to be perfectly adapted for culture of infectious respiratory disease. Additionally, there is poor vascularisation of the air sacs, thus parenteral treatment of air sac disease is problematic. Pneumatisation of bones, between muscle bodies and subcutaneously may allow the spread of respiratory diseases to abdominal organs, bone or soft tissues. Common diseases localised in the air sacs include aspergillus, bacterial infections (especially coliforms) and chlamydia.

Macrophages and heterophils are poorly represented in the avian lung system in comparison to mammals. Their resident numbers in bird lungs are only 5% that in mammalian lungs however recruitment into the lungs can be rapid.

Inhalation of foreign material, whether inert or infectious, is a common cause of respiratory disease in birds. The size of an inhaled foreign body strongly influences the predicted site of deposition. Larger bodies will tend to be deposited by inertial impaction in the upper respiratory system, most commonly in sites where the air flow is slowed, including tracheal bends, the syrinx and the caudal end of the primary bronchi. Smaller bodies may be deposited in the same sites, but may also accumulate in the caudal air sacs and parabronchi by gravitational sedimentation. Understanding of species difference is important in predicting where such foreign bodies may initiate disease. Birds with more complex syrinxes or convoluted and / or elongated tracheas may be at higher risk for foreign body associated disease in these areas.

Considerations before inhalant anaesthesia

Inhalant general anaesthesia is a commonly used tool in avian medicine. Rapid improvements in techniques and agents have occurred over the past 20 years, with a subsequent significant drop in associated morbidity and mortality. Isoflurane or sevoflurane administered though low dead space, non-rebreathing systems has become routine. Positioning of patients and the use of masks or intubation remain more difficult decisions.

The ideal positioning of the patient during anaesthesia remains difficult, with recently published papers providing conflicting findings from different species. Given the need for the keel to move forwards and upwards to provide negative pressure during inspiration, ventral recumbency is generally considered contra-indicated. However, studies of air sac and lung volumes in anesthetised penguins and hawks found that ventral recumbency caused less reduction in air sac volume than dorsal recumbency. Right lateral recumbency was found to provide the least alteration in air sac volume. Lung volume was not significantly affected by positioning. Blood gas analysis was not performed in the penguins. In hawks, dorsal recumbency maintained higher PO2 than right lateral recumbency despite smaller air sac volumes. Blood gases were not assessed in ventral recumbency. Clearly, more work needs to be performed to determine ideal positioning during anaesthesia, and if this is species dependant.

The choice to intubate or not, tube design and depth of placement is something which needs to be assessed on an individual case basis. Intubation has the advantages of securing the airway (protecting against regurgitation / inhalation etc) and allowing IPPV. However, there is a risk of inducing post intubation tracheal obstruction (see below) and the small tube diameter needed in many species can risk obstruction of the tube with mucous. The most common alternative is to use face mask administration. Face mask administration does not provide a secure airway but may allow some IPPV. A newer alternative is the use of laryngeal mask administration. Laryngeal masks allow the use of IPPV, but do not protect completely against regurgitation / inhalation. Careful stabilisation and monitoring of the contact of the mask with the larynx is required. Laryngeal masks are not available for smaller avian species at this time, but new products are being released for small exotics, and this is an area worth watching.

Post intubation tracheal obstruction appears to be a relatively uncommon sequella of intubation, but carries significant morbidity and mortality. In one zoological setting study, between 2 and 8% of intubations resulted in tracheal obstruction of variable severity, with an overall mortality rate of 70%. Clinical presentation was 7-21 days post intubation. Potential contributors to post intubation tracheal obstruction include mechanical trauma, chemical irritation (including from sterilisation liquids and gases), duration of intubation, dry gases, high gas flows rates and the use of positive pressure ventilation. Possible variation in risk between species has been suggested by one author with Gruiformes, Anseriformes Galliformes and Passeriformes at higher risk and Falconiformes, Coraciformes and Psittaciformes at low risk. This may reflect anatomical differences, with a more dramatic narrowing of the trachea between the glottis and the syrinx in some species, as well as an increased risk of mechanical trauma in long-necked birds.

When tracheal access is difficult during anaesthesia, due to obstruction of the surgical field or obstruction of the trachea or syrinx, air sac cannulation can be utilised to provide anaesthesia. In the case of tracheal or syrinx obstruction, air sac cannulation can also be used for emergency stabilisation of patients, by bypassing the obstructed area and allowing adequate ventilation. Low flow rates (0.3 ml/kg/min) +/- oxygen and nitrous oxide mixtures are recommended for air sac anaesthesia to minimise the decrease in arterial PCO2 and induction of alkalosis, the first of which can lead to apnoea and the latter cardiac arrhythmias. Despite low flow rates, apnoea may occur if the trachea is patent. Pulse oximetry is important in monitoring anaesthesia in apnoeic patients. Isoflurane concentrations may need to be higher than when using tracheal administration especially if the trachea is patent. Exhaled gases require scavenging to minimise human health risks. Air sac administration of anaesthesia results in lower arterial and venous PO2 than routine ET tube administration, but excellent saturation is maintained.

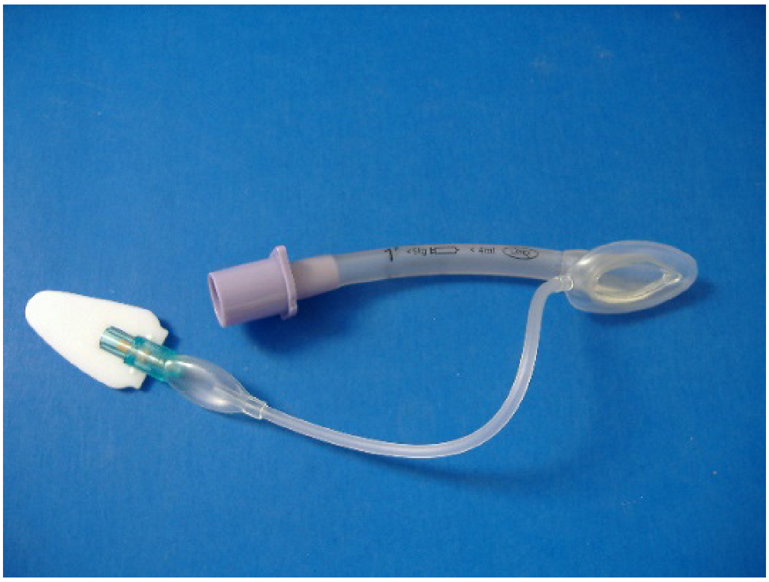

Figure 7: Neonatal laryngeal mask

http://resus.me/lma-for-newborn-resuscitation/

Figure 8a: Radiograph of a duck with an air sac cannular placed
Courtesy Professor Bob Doneley, Universtity of Queensdland

Figure 8b: Radiograph of a duck with an air sac cannular placed
Courtesy Professor Bob Doneley, Universtity of Queensdland

Further reading

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