2. DEMONSTRATIONS OF ASPHYXIA AND RESPIRATORY MECHANICS IN AN ANAESTHETIZED RABBIT

THIS IS PRESENTED AS A VIDEO IN A TUTORIAL

The preparation consists of an anaesthetized rabbit with femoral artery and femoral vein catheters and a tracheostomy tube. The pleural pressure is demonstrated during various respiratory manoeuvres recording directly via an air-filled intra-pleural catheter inserted through the chest-wall. The small air-bubble in the pleural space provides the pressure indication, via the catheter and a water-filled manometer. The preparation is deliberately kept very simple without any electronic "black-boxes" to obscure the main messages.

1. Pleural pressure is seen to be sub-atmospheric at the end of expiration and to become more negative during inspiration.

2. During inspiratory efforts against an obstructed trachea, pleural pressure becomes very negative, reflecting a fall of both pleural pressure and alveolar gas pressure (the pressure which is due to lung recoil, must of course remain constant since lung volume does not change in this manoeuvre).

3. The lung recoil, which is normally balanced by the transpulmonary pressure (pleural pressure in relation to inside alveolar gas pressure), is demonstrated by opening the pleural catheter to atmospheric pressure and observing that the lung collapses; in this animal preparation both pleural cavities can be widely opened to atmospheric pressure and both lungs are seen to be completely collapsed. The concepts of lung recoil and transpulmonary pressure are demonstrated by showing that the lungs can be re-expanded by either sucking air out of the pleural cavity and restoring the normal sub-atmospheric pleural pressure, or by making the pressure inside the lungs above atmospheric, i.e. mouth-to-mouth or intermittent positive pressure ventilation. Either method provides the appropriate transpulmonary pressure, i.e. a pressure difference across the lung surface to oppose lung recoil. The standard clinical method of providing a positive pressure inside the lungs is by a respirator; this intermittently provides a positive pressure at the entrance to the air-way; this mouth pressure is reflected (with some reduction due to airflow resistance) as a positive alveolar gas pressure. By intermittently restoring atmospheric pressure at the airway entrance, lung recoil produces passive expiration.

Another point: following thoracic surgery, air normally remains in the pleural cavity; this is expelled as far as possible by inflating the lungs with positive pressure; when pleural pressure rises above atmospheric pressure, air will be forced out through the catheter in the chest-wall and can be prevented from returning if a one-way valve is provided; the simple one-way valve used in practice consists of a water-seal, i.e. dipping the end of the catheter below water in a bottle; when air is expelled from the pleural cavity, it bubbles out under the water and sub-atmospheric pleural pressure will be re-established and of course the water level rises up the catheter (for this reason the bottle must be safely positioned well below the bed). It is important to remember that pleural pressure can also become positive during coughing and this is the normal respiratory manoeuvre which expels air from the pleural cavity via a catheter.

The following notes list a series of experimental manoeuvres, followed by questions related to the observed responses and to the underlying physiological mechanisms; in each case, the experimental technique is identified by Italics.

Preliminary observation of normal breathing
Why is the pleural pressure at end-expiration about -3cm of water and about -6 cm H₂O at end-inspiration?
The trachea is occluded with the finger (at end expiration) for several breaths. Why is this pressure about -20 cm of water at the first obstructed breath?

Why did the water-manometer indicate progressively increasing negative pleural pressure swings at each inspiration for example -20, -25, -30 cm H2O etc.?

In a normal unobstructed breath, the expansion of the lungs excites pulmonary stretch receptors (afferents in the vagi) which reflexly inhibit the crescendo activity of the brain-stem inspiratory centre and normally terminate this activity. In the absence of lung expansion, the inherent brain-stem inspiratory activity is unopposed and the inspiratory effort is manifest as a marked negative pressure swing in the pleural space, as the chest-wall attempts to expand and pulls on the surface of the lung; the negative pleural pressure swing is also reflected as a negative pressure swing in alveolar and airway pressures (at constant lung volume, the difference between pleural and alveolar pressure is constant and determined by lung elastic recoil).

The breath-by-breath progression of the negative pleural pressure swings is the result of rapidly developing asphyxia and stimulation of the carotid bodies (by hypoxia) and stimulation of the brain-stem "respiratory centre" (by the rising CO2 tension). Hypoxaemia is seen by examination of femoral arterial blood. The CO2 stimulus can be inferred since breath-by-breath progression (still present but markedly reduced) persists in this experiment when the animal is pre-treated with 100% O2 prior to tracheal occlusion.

In the latter experiment we again examine femoral arterial blood and observe a bright red colour indicating maintained saturation of haemoglobin. This simple physiology highlights the rationale of pretreating patients about to undergo induction of anaesthesia, with 100% O2. In such patients, there is always the risk of vomiting at the onset of anaesthesia and airways obstruction; disastrous hypoxaemia will be avoided for several minutes at least (during suction of vomitus from the trachea) providing the lungs contain a large store of 100% O2.

If arterial blood is not available to examine for the presence of hypoxaemia, what observations can we make?

What is the difference between central and peripheral cyanosis?

The tracheostomy tube is connected to an intermittent positive pressure respirator which is set to ventilate the rabbit at a rate and depth in excess of normal.

Why does the animal appear to "fight" the respirator initially? (By "fighting" we mean the animal is attempting to breathe spontaneously out of phase with the intermittent positive pressure so that sometimes the animal is attempting to expire when the machine is attempting to inflate the lungs.)

Why do all spontaneous respiratory efforts cease after several minutes?
Why does the rabbit remain apnoeic for several minutes, after disconnecting the respirator?

Why does this period of apnoea persist for a much longer period when the respirator is set to deliver 100% O₂ in the preceding period of hyperventilation?

These simple experiments nicely demonstrate that hyperventilation lowers the arterial blood PCO₂ and ultimately the brain-tissue CO₂ tension below normal values; the reduced CO₂ tension in the brain-stem reduces the normal " CO₂-stimulus" to breathing below the threshold for spontaneous breathing and this accounts for the apnoea.

After disconnecting the respirator, metabolic CO₂ gradually refills the blood and tissue CO₂-stores and eventually restores the normal CO₂-stimulus to breathing. Simultaneously the O₂ tensions are falling and in the experiment in which the animal was ventilated with air, the O₂-stores (air in the lungs) are very small. Since body CO₂-stores are relatively large they fill slowly and the hypoxaemic stimulus to breathing develops before the restoration of a normal CO₂-stimulus and in these circumstances the resumption of spontaneous breathing is produced by hypoxaemia at the carotid bodies. When the lungs are enriched with O₂ this hypoxaemia is greatly delayed and, in most cases, CO₂-stores will have time to refill, and the CO₂-stimulus will initiate breathing.

These simple physiological observations are of great importance in clinical practice since it is desirable to over-ventilate anaesthetized patients in many forms of surgery (e.g. during neuro-surgery, since a greatly reduced arterial CO₂ tension results in a marked reduction of cerebral blood flow, minimizes bleeding and shrinks the brain in the skull and thereby facilitates clear vision for the surgeon). Obviously at the end of such an operation, it is essential to restore the normal CO₂-stimulus to breathing and to restore spontaneous breathing efforts, without exposing the patient to the risks of hypoxaemia during apnoea.

**The lungs are inflated by manual compression of an O₂-filled bag connected to the tracheostomy tube.**

Why does the breathing rhythm cease, as judged from pleural pressure and respiratory muscle movement?

The mechanism is fairly obvious when we observe that breathing-rhythm continues uninterrupted in this experiment after bilateral vagotomy!!

The positive pleural pressure in this experiment also reminds us that the pleural pressure is not always below atmospheric; another circumstance producing positive pleural pressure is coughing or expiratory effort against a closed glottis. (The text-books seem to imply that pleural pressure is always sub-atmospheric).

Pleural pressures above atmospheric are very important in clinical medicine because this allows air in the pleural cavities (e.g. after thoracic surgery or after a spontaneous pneumothorax from a ruptured "cyst" on the surface of the lung) to be forced out through a pleural catheter. The catheter is normally provided with a "one-way valve" by dipping it below the surface of water in a bottle below the patient's bed. Obviously, as air is expelled from the pleural cavity in a series of coughs, the normal subatmospheric pressure is re-established in the pleural spaces and this will be reflected by rising water levels in the pleural catheter. It is essential to have the bottle well below the patient to avoid water being sucked back into the pleural spaces. Pleural pressure is an important concept!!
The pleural catheter is opened to atmospheric pressure

Why does the animal make progressively increasing inspiratory efforts?

The two factors here are blood gases and reduction of stretch-receptor discharge from the collapsed lung. Sometimes when we examine femoral arterial blood with one lung collapsed, we are surprised to find a relatively normal O₂-saturation. In this case, the 'veno-arterial' or 'right-to-left' shunt (blood flowing through a non-ventilated lung) is minimized by pulmonary arterial vaso-constriction; this originates as a local action of hypoxaemia on smooth muscle in pulmonary vessels, since the effect persists in the denervated lung. The vaso-constriction in the collapsed lung diverts blood to the well-ventilated opposite lung, and thereby minimises systemic arterial hypoxaemia.

Both lungs are collapsed simultaneously by splitting the sternum and opening both pleural cavities to atmospheric pressure

In this preparation, intermittent positive pressure can be applied to the tracheostomy by a respirator, or by "mouth-to-tube resuscitation", to produce ventilation of the lungs.

Why does the diaphragm contraction greatly increase in amplitude and frequency when both lungs are collapsed and ventilation ceases?

Why does this progressive augmentation of inspiratory effort eventually cease, i.e. apnoea?

These simple experiments nicely demonstrate the fact that hypoxaemia stimulates the carotid bodies and inspiratory efforts on one hand, but on the other hand leads to non-specific depression of all C.N.S. function. Eventually the latter effect dominates and the brain-stem respiratory centres are completely depressed despite the very powerful stimuli of the elevated CO₂ tension acting on the medullary chemoreceptors, and the severe hypoxia acting on the carotid bodies.

We notice that respiration fails before complete collapse of the cardio-vascular system; the heart continues to beat after complete cessation of all respiratory movements and this corresponds with the classical description in the text-books (e.g. in drowning). A single inflation of the lungs by elevating arterial O₂ tension leads to a prompt restoration of spontaneous breathing (seen in the resumption of vigorous diaphragmatic movements).

The severe asphyxia is not without catastrophic effect in the cardio-vascular system, however. We observe gross dilatation of the heart, especially of the ventricles, indicating failure of contractility of the myocardium, when the CO₂-supplies to the heart fail. Failure of effective ejection is seen as a marked fall of arterial pressure. We commonly also observe failure in the specialized conduction-tissue, with the development of varying degrees of "heart block"; e.g. the ventricles may be beating slowly under the influence of the A.V. node and quite independently of the atria; sometimes we see every 2nd atrial systole associated with conduction to the A.V. node, with one ventricular systole for every 2 atrial contractions.
DISCUSSION QUESTIONS

1. How is pleural pressure measured?

2. Why is it normally subatmospheric?

3. What is the effect of diaphragmatic contraction on pleural pressure?

4. How was diaphragm electromyogram measured?

5. What is the effect of occluding the trachea for one breath on diaphragm electromyogram and pleural pressure?

6. Briefly explain the mechanism of immediate load compensation.
   i)
   ii)
   iii)

7. Describe the pathway of the bronchial stretch receptors.

8. What happens when they are stimulated?

9. If the rabbit’s trachea is occluded for 30sec, what happens to the colour of the blood? Why?

10. Would things be different in a human baby? An adult? Why?
11. The carotid body detects several physiological stimuli, two of which were mentioned in the video. List these and any others that you know.

12. Why does inspiratory effort increase yet further with prolonged tracheal occlusion?

13. The carotid body provides reflex defenses against asphyxia. Describe the pathways involved and how they help physiologically.

   i)

   ii)

   iii)

14. Preoxygenation increases lung oxygen stores. Why does it not also usefully increase blood oxygen stores?

15. Five seconds ago, you gave a general anaesthetic to a very obese patient, and you find that you cannot maintain their airway: oropharynx is totally occluded. You attempt to insert an endotracheal airway, but you are finding it extremely difficult. However, you are not panicking because:
   a) It’s not really your patient
   b) You have your plane ticket with you
   c) Seriously, you have taken the precaution to:

16. How will this help?

17. When the rabbit was pre-oxygenated, it took much longer for the blood to go dark, but the respiratory effort increased even while the blood was still bright red. Why?

18. Draw a sketch of the lung and blood $O_2$ and $CO_2$ stores under the following conditions:

   i) increased rate and depth compared to normal
   ii) decreased rate and depth compared to normal
19. What is the effect of recent overbreathing on spontaneous ventilation?

20. Is this due to hyperoxia or hypercapnia? Why?

21. After Hyperventilation, the rabbit stopped breathing, and then started breathing again some time later. Why did the rabbit start breathing again?

22. Sketch the stores at the moment of recommencement of breathing.

23. You are the anaesthetist again. You have paralyzed the patient with pancuronium, and ventilated them artificially during the surgery. Now you have correctly reversed the pancuronium with neostigmine, but the patient won’t resume spontaneous breathing. Why not?

24. What steps should you take? (You may NOT leave the country.)

25. The rabbit’s lungs are mechanically held inflated. What is the immediate effect on the diaphragm electromyogram? Explain.

26. Why does breathing start again even though inflation is maintained?

27. What happens to spontaneous breathing if you cut the vagi?

28. What happens to the diaphragm electromyogram if you inflate the lungs mechanically after the vagi are cut?

29. What is a pneumothorax? How can you get one?
30. A pneumothorax can lead to severe hypoxia?

31. What important local reflex can help minimize the hypoxia? How?

32. How can you treat a simple pneumothorax?

33. How does a tension pneumothorax differ from a simple pneumothorax?

34. Why is a tension pneumothorax an extreme emergency?

35. What is the role of the upper airway dilator muscles?

36. What happens if the genioglossus fails to contract?

37. What happens to the genioglossus activity when you block the trachea?

38. Explain.
   i)
   ii)

39. What factors depress the reflex control of the upper airway?

40. Why do drunks snore?

41. Why do you need an artificial airway when deeply anaesthetized?
42. What happens to the lungs if the pleural cavities are open?

43. How can you inflate the lungs if the pleural cavities are open?

44. Assume the vagi are cut. What happens to the blood pressure during moderate asphyxia?

45. What happens if asphyxia becomes overwhelming? Explain.

46. What happens if you then administer a few breaths of oxygen?

47. What happens to the diaphragmatic efforts during moderate asphyxia? Explain.