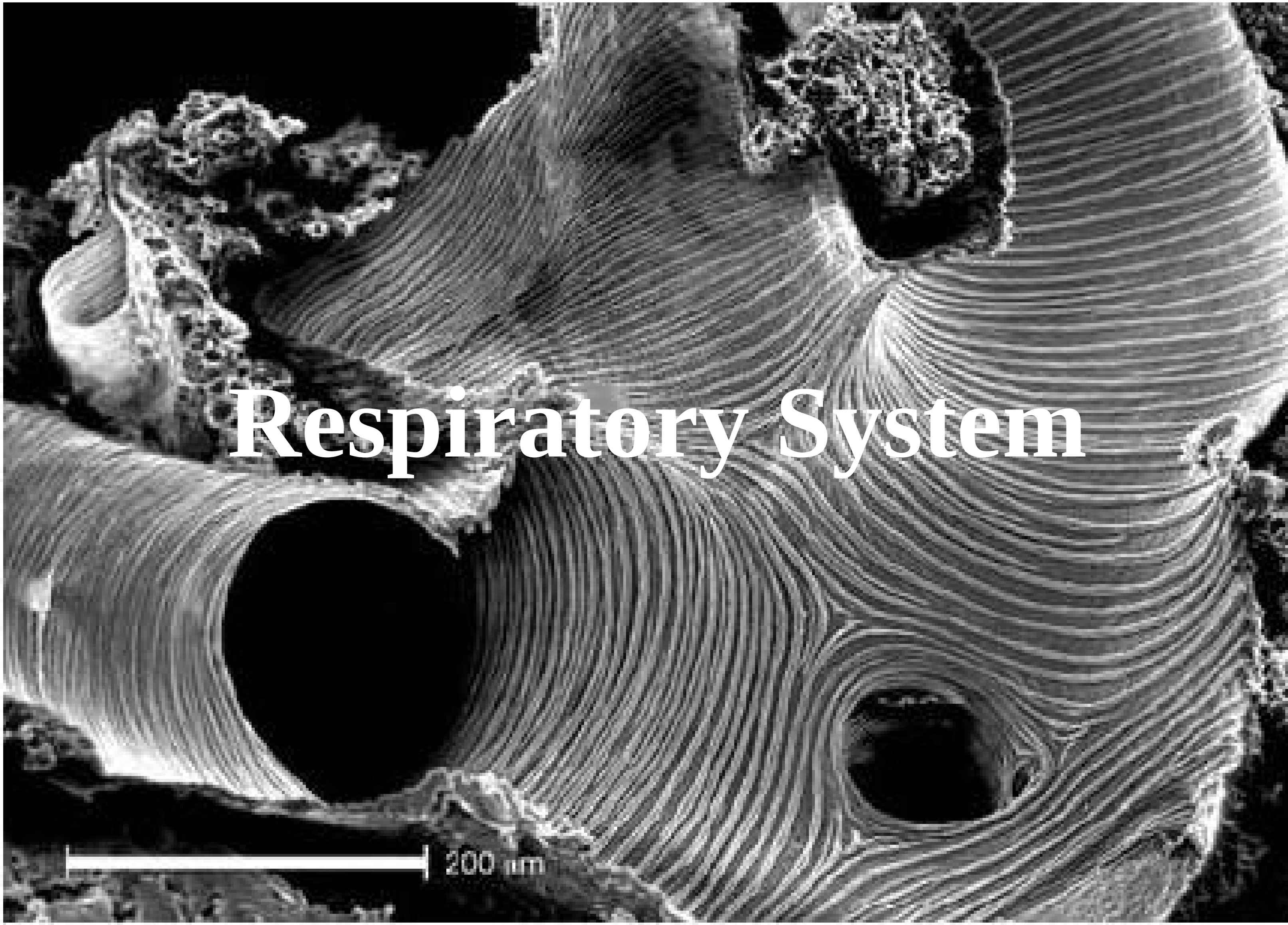
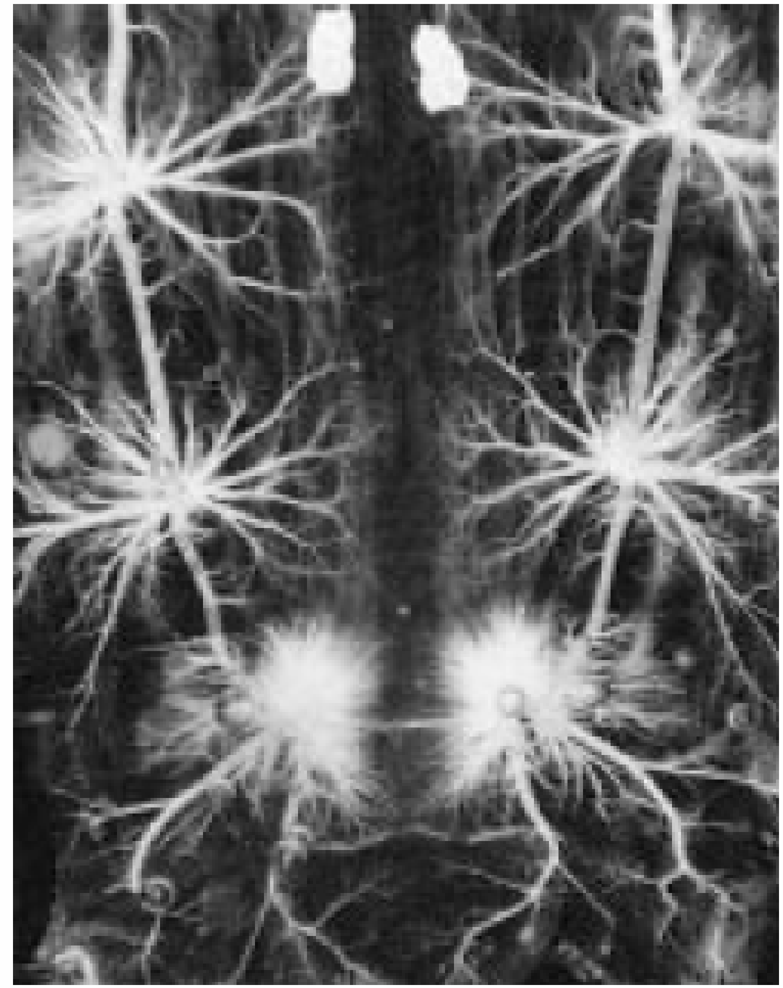
Respiratory System



Caterpillars have lungs

Figure 1 Alice confronts one caterpillar that clearly has lungs.

(Mill 1998 after Carroll 1866)



Inside view of the “lung”

(Locke 1998)

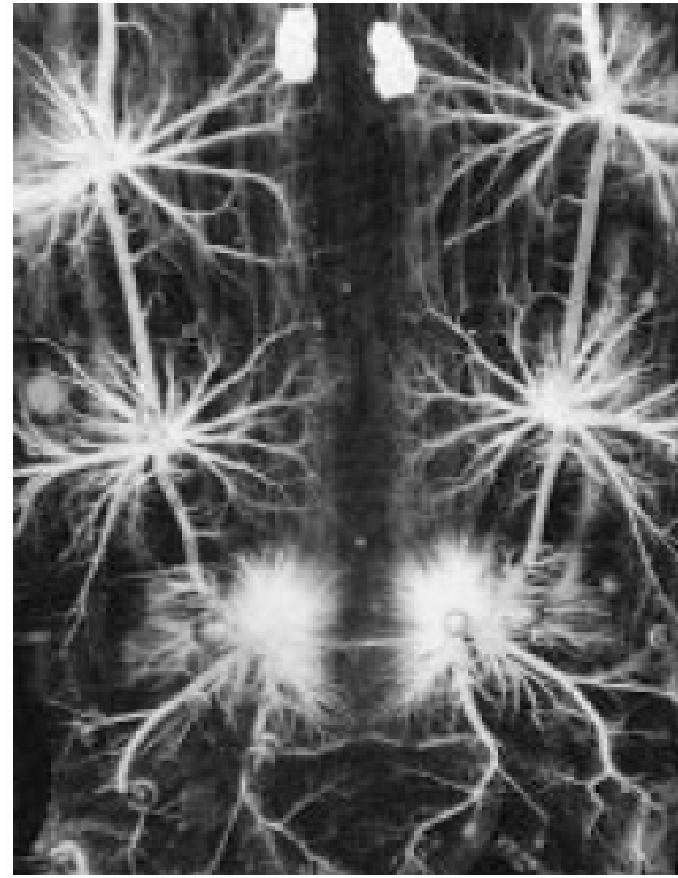
Locke's caterpillar of choice

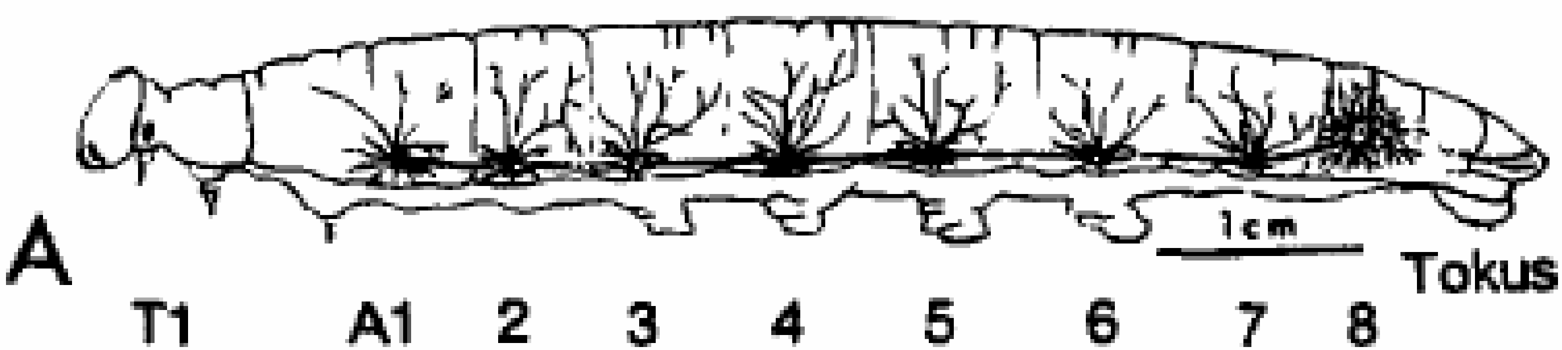
Brazilian skipper or Canna leafroller, *Calpodes ethlius* (Stoll) (Lepidoptera; Hesperiidae)

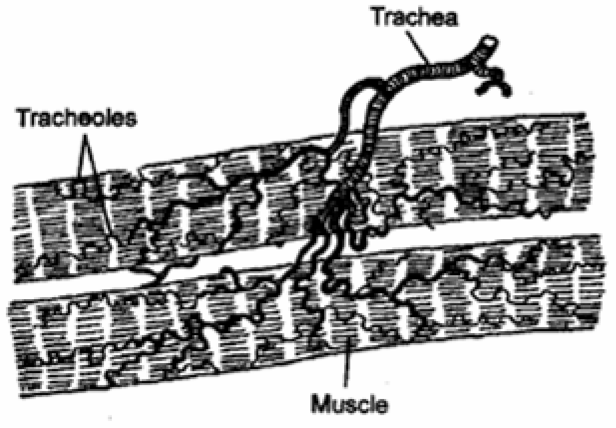
Larval Photo by Drees. http://insects.tamu.edu/fieldguide/cimg264.html
Adult Photo by Paul Opler http://www.npwrc.usgs.gov/resource/distr/lepid/bflyusa/sc/461.htm

In *Calpodes* and larvae from 13 other families of Lepidoptera

- **Most have spiracle 8 large than spiracle 7**
- **All have tufts associated with 8th spiracle**
- **All has a distinct pattern of tracheation in the telson**



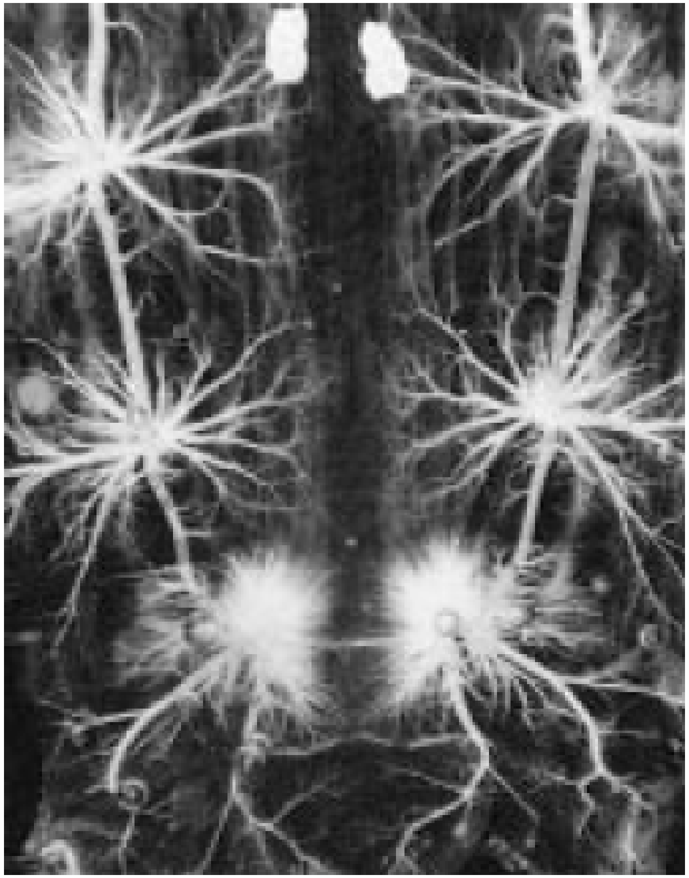




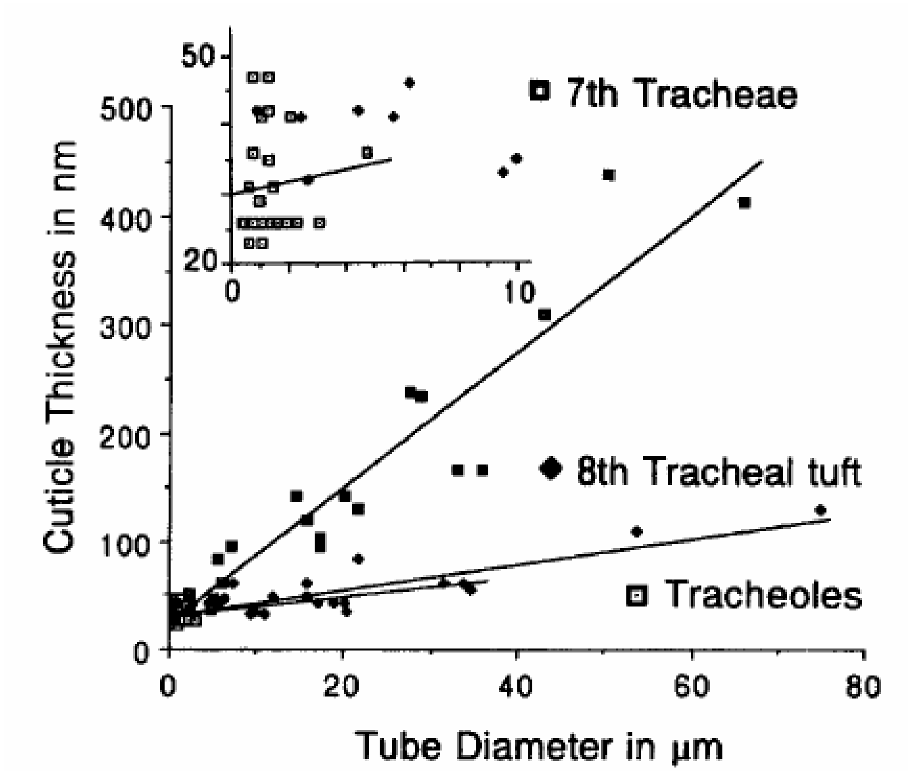
Gaseous exchange occurs through tracheoles that penetrate between cells.

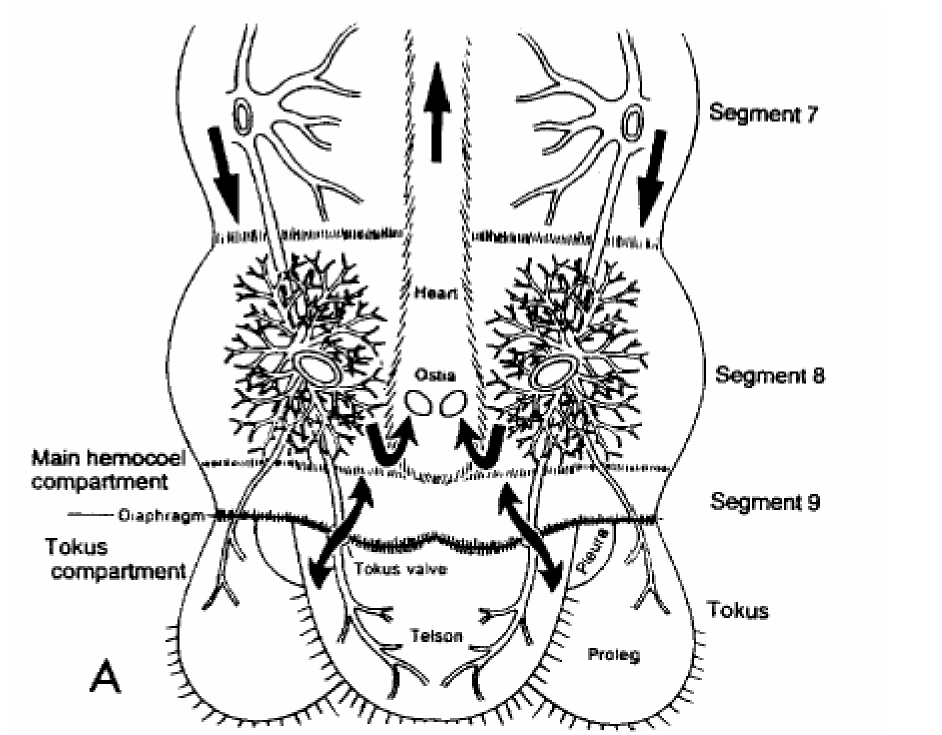
Not all tissues are permanently tracheated (i.e. hemocytes)

Not all trachea supply cellular tissues (i.e. tufts at spiracle 8)



The tracheal system in the last three segments of a live caterpillar.



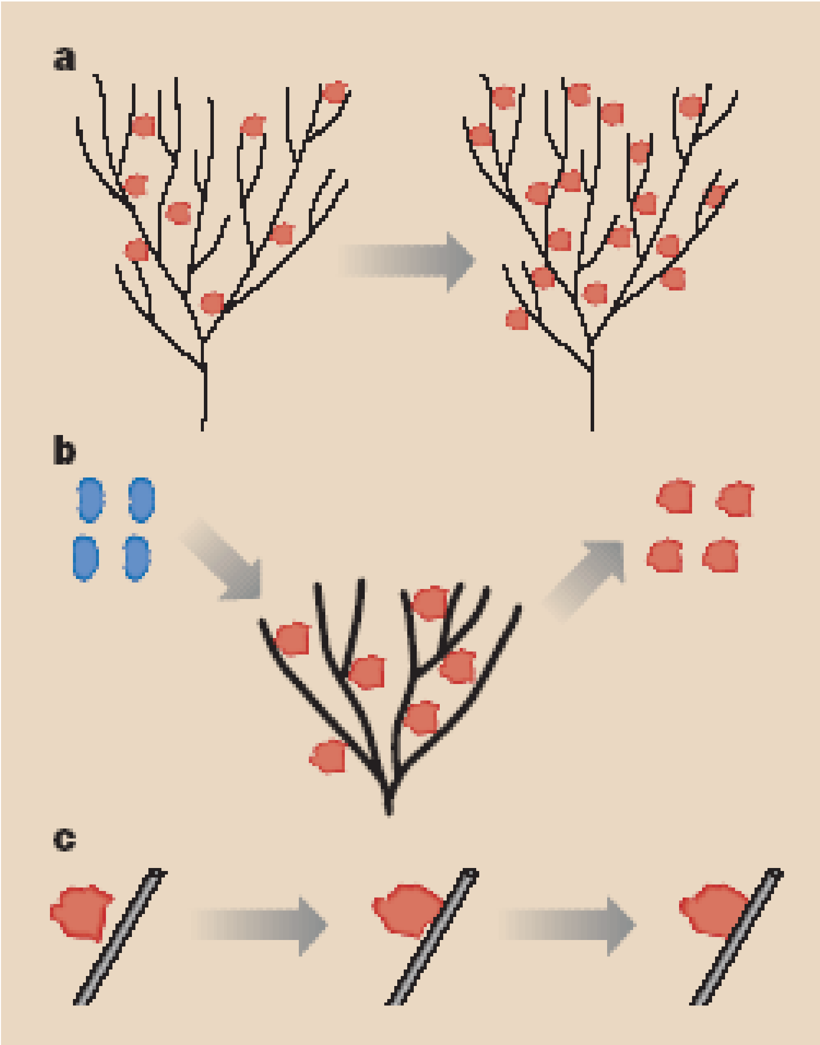


How do tufts differ from trachea in other segments?

- Terminal tracheoles turn back on themselves and end in knots in hemolymph
- Cuticle between the taenidia is very thin
- Attachment to muscle and connective tissue strings suspending the heart keep tufts in constant motion
- Aerating trachea

(Locke 1998)

The branched tufts of trachea and tracheoles that provide blood cells with oxygen



(Mill 1998)

a) **The number of hemocytes (red) in a tuft increases when a caterpillar is subjected to oxygen starvation.**

b) **Oxygen-starved granulocytes (blue) entering a tuft resume the characteristics of those in a well-oxygenated environment (red).**

c) **In the tokus – a 'lung'-like compartment — the hemocytes become closely apposed to the thin-walled tracheae and tracheoles.**

Common misconception:
Insect tracheal system is inefficient at transport of gases

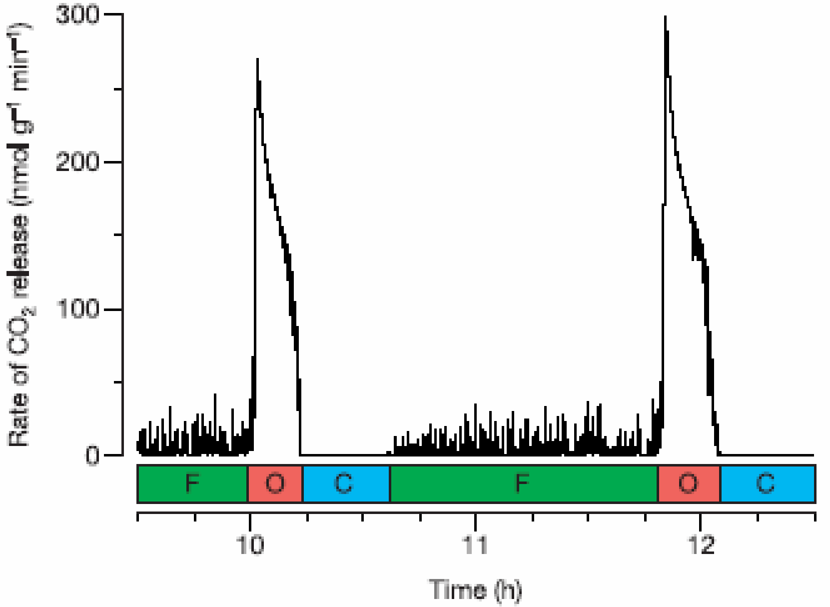
Reality:
Oxygen is delivered 200,000 times faster and carbon dioxide 10,000 faster than in blood.

The largest insects know to exist would get adequate oxygen supply and carbon dioxide removal through simple diffusion (e.g *Meganeura monyi*, ancient dragonfly with a wingspan of 70cm, lived 280 mya)

Burmester 2005

Discontinuous gas-exchange cycle:

Spiracles remain closed for hours or days and open occasionally for a few minutes



The rate of release of CO2 from a pupa of *Attacus atlas* over time.

Hetz and Bradley 2005

•A burst of CO2 release is observed during the open phase (O, red bar). Open phase is initiated by critically high CO2.

•During the closed phase (C, blue bar), the spiracles are closed and CO2 release is low.

•The closed phase is followed by a flutter phase (F, green bar) during which CO2 release occurs in brief intervals. Flutter phase is initiated by critically low levels of O2.

Why do insects stop breathing?

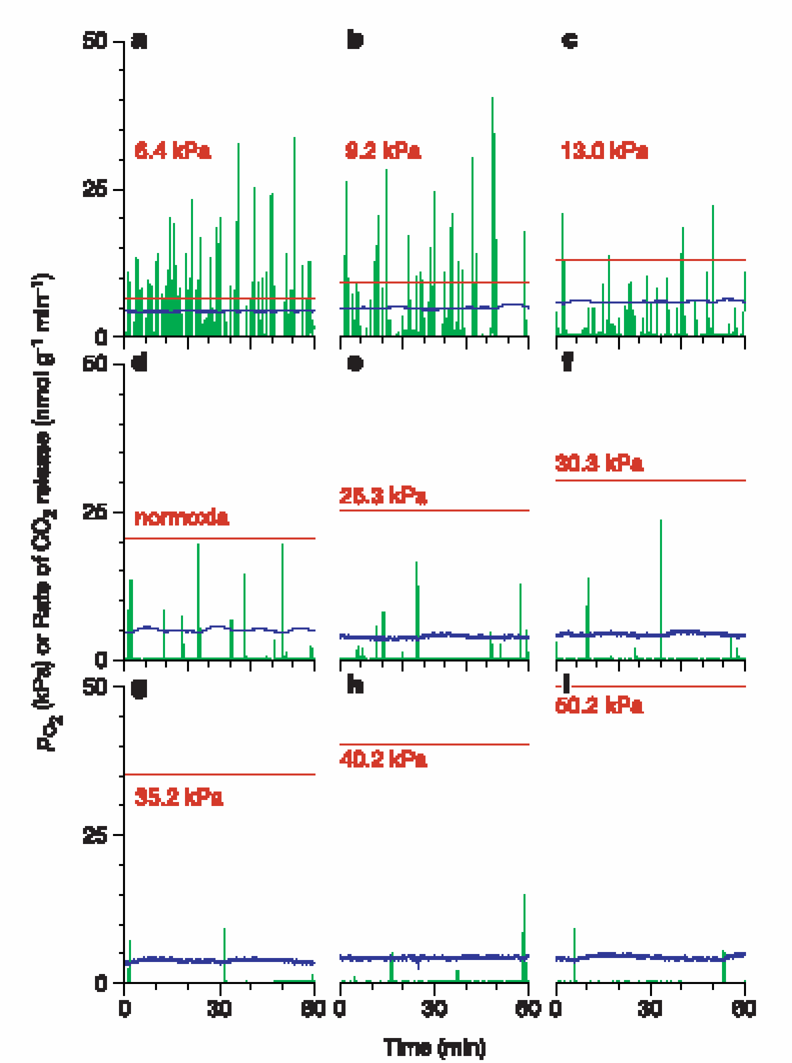
1) Reduce water loss through the spiracles

2) Adapt to an under ground life style

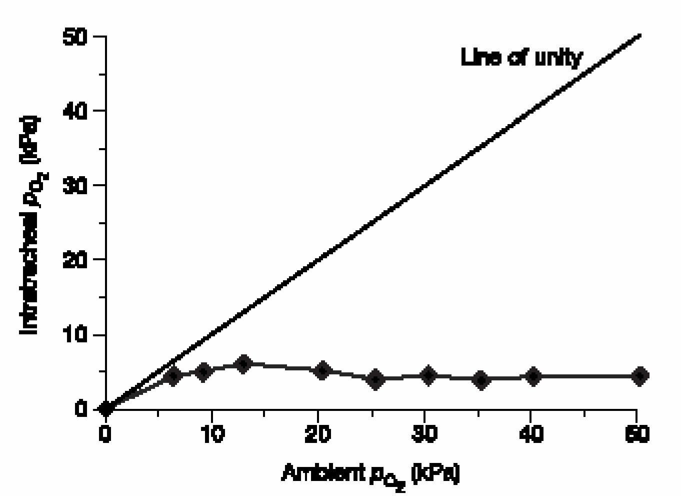
3) To avoid oxygen

Oxygen is a double-edged sword.

- Reactive oxygen species can damage proteins, DNA, and lipids.
- Sufficient oxygen levels are required for efficient mitochondrial respiration.



As Hetz and Bradley varied the O_2 concentrations from 5 to 50 kPa, the intra-tracheal oxygen levels remained low- close to 4 kPa.



Green lines- CO_2 released by insect

Red lines- ambient O_2

Blue lines- O_2 in insect trachea

The insect respiration system has been designed to function most efficiently at high levels of O_2 consumption.

The DGC respiratory pattern is the insect's attempt to use a high capacity system during periods of "metabolic idling".
DGC is observed only in resting insects.
DGC disappears when insects increase their metabolic rate when cells use oxygen at a faster rate.

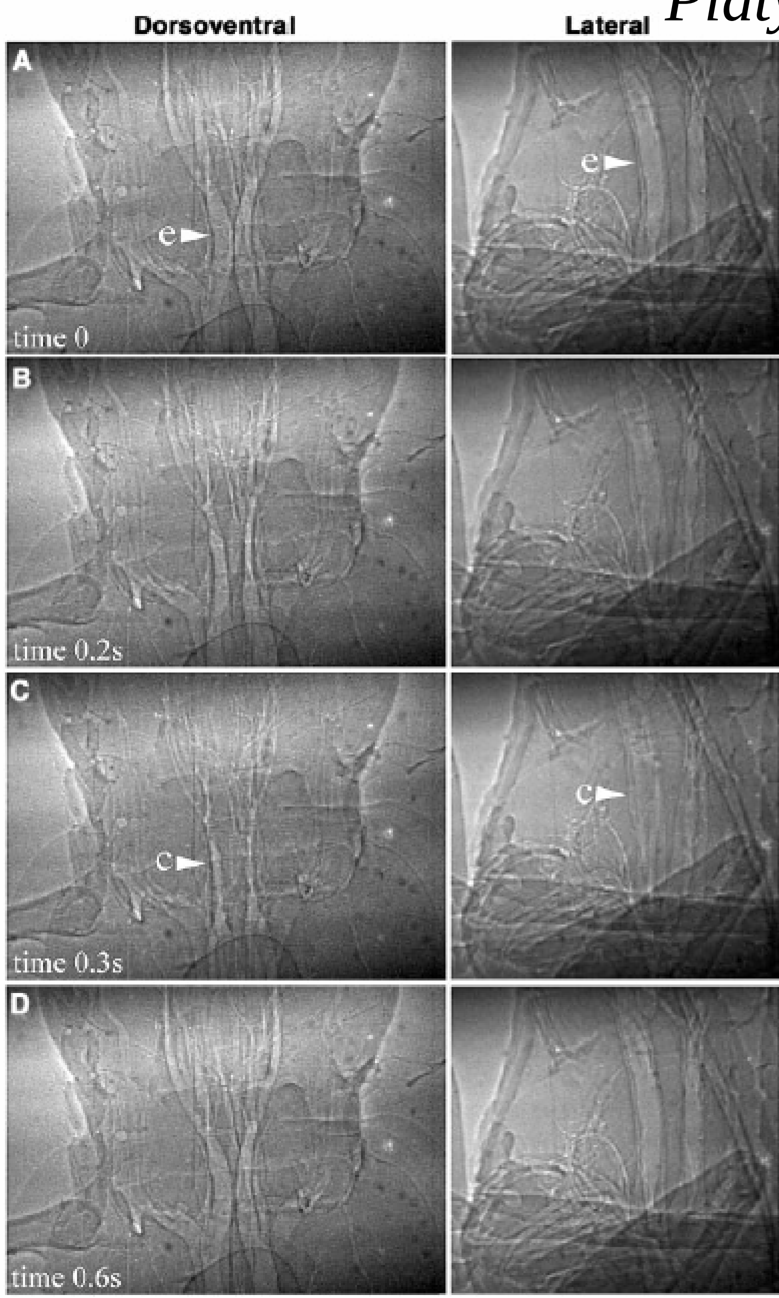
Mechanisms for insect respiration:

- Passive gas diffusion (Krogh 1920)
- Changes in internal pressure due to hemolymph pumping by heart or by muscle contraction (Wasserthal 1996)
- Autoventilation- body movements change volume of tracheal tubes or air sacs (Slama 1999)
- Compressing and expanding the trachea (like the way vertebrates fill their lungs)

Misconception:
Insect cannot breathe

Use technology to visual insects breathing
A synchrotron, a circular particle accelerator that can generate x-rays was used to look inside living insects.
Videos of the movements can be created.

Respiration by tracheal compression in the head and thorax of beetle *Platynus decentis*



A- tracheal tubes expanded at rest arrowhead e
B-compression occurs throughout the anterior region of the insect
C- maximal compression Arrowhead c
D- compression followed quickly by expansion of the trachae

Entire cycle takes less then 1 second

Westneat *et al.* 2003

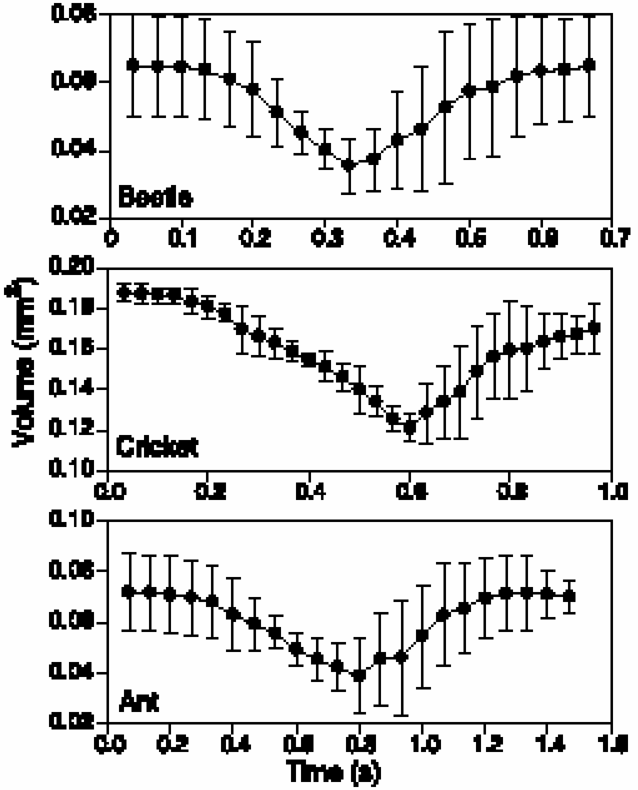


Fig. 3. Volume change in the main tracheae of the anterior thorax and head of the wood beetle, house cricket, and carpenter ant during respiratory cycles. Error bars, standard deviation of the mean of three respiratory pumping events in different individuals.

Advantages of rapid, active breathing mechanism

•Rapid conduction of gases when insects are respiring at high rates (e.g. stress, flight, locomotion)- 50% volume change

•Aide oxygen diffusion to tissues- increased pressure will raise the diffusion gradient of oxygen across the tracheole-tissue boundary when spiracles are closed

Westneat *et al.* 2003

Breathing observed in:

Endopterygotes (beetles, butterflies, flies)
Hemiptera, Orthoptera, Dermaptera, Blattodea, and Odonata

Mechanism of tracheal compression

- Contraction of jaw or limb muscles cause elevated pressure inside the exoskeleton
- When muscles relax the tracheae expand due to support from rings of taenidia in the tracheal wall

Active tracheal breathing may have played an important part in the evolution of terrestrial locomotion, running performance, and flight in insects, and it may be a prerequisite for oxygen delivery to complex sensory systems and active feeding mechanisms.

Burmester, T. 2005. A welcome shortage of breath. Nature. 433: 471-472

Hetz, S.K. and T.J. Bradley. 2005. Insects breathe discontinuously to avoid oxygen toxicity. Nature. 433: 516-519.

Locke, M. 1998. Caterpillars have evolved lungs for hemocyte gas exchange. Journal of Insect Physiology. 44(1):1-20.

Mill, P.J. 1998. Caterpillars have lungs. Nature. 391:129-130.

Slama, K. 1999. Active regulation of insect respiration. Annals of the Entomological Society of America. 92 (6): 916-929.

Westneat, M.W., Betz, O., Blob, R.W., Fezzaa, K. Cooper, W.J., and W-K. Lee. 2003. Tracheal respiration in insects visualized with synchrotron x-ray imaging. Science. 299:558-560.