OUTLINE

• Avian respiratory system
• Avian circulatory system
• Metabolism
• Thermoregulation
• Excretion

THE RESPIRATORY SYSTEM

• Avian respiratory system is unique among vertebrates
• Most efficient in animal kingdom beside fish gills
• Primary function of lungs is to provide oxygen and remove carbon dioxide from tissues
• Secondary function is thermoregulation — birds do not have sweat glands

THE RESPIRATORY SYSTEM - MAMMALS

• Mammal lungs are inherently inefficient because they are "tidal" versus the flow through system in birds
• In mammals, lungs are dead-end air sacs so the air moves in and out via the same pathway
• Therefore, fresh air is mixed with deoxygenated stale air and some of the air is re-breathed
• Mammals cannot exhale 100% of the air in the lungs (20% remains)

THE RESPIRATORY SYSTEM - BIRDS

• Lungs of humans occupy about 5% of body volume
• Lungs and air sacs occupy 15% of birds body volume

THE RESPIRATORY SYSTEM - STRUCTURES

• TRACHEA — connects to syrinx
• SYRINX — organ of sound production
• BRONCHI — paired tubes that branch off the syrinx and connect to each lung
  — Interconnecting bronchial tubes form the internal structure of the birds lung

THE RESPIRATORY SYSTEM - STRUCTURES

• AIR SACS — thin walled structures that extend throughout the body cavity and into the wing and leg bones
  — Connected directly to bronchi
  — Make continuous, unidirectional air flow possible
• Also help remove body heat and protect organs
• Most species have 9 air sacs
THE RESPIRATORY SYSTEM - STRUCTURES

- THORACIC AIR SACS
  - Paired air sacs in the thorax

- ABDOMINAL AIR SACS
  - Paired abdominal air sacs

- INTERCLAVICULAR AIR SAC
  - Single air sac
  - Branches penetrate the wing bone
  - Pressure from this air sac on the syrinx is essential for vocal sound production

FUNCTION OF THE RESPIRATORY SYSTEM

1 - On first inhalation, air flows through the trachea & bronchi & primarily into the posterior (rear) air sacs

2 - On exhalation, air moves from the posterior air sacs & into the lungs

3 - With the second inhalation, air moves from the lungs & into the anterior (front) air sacs

4 - With the second exhalation, air moves from the anterior air sacs back into the trachea & out
OTHER FUNCTIONS OF THE AIR SACS

- Thermoregulation - approximately 20% of a bird's heat production can be lost through evaporative cooling via air sacs
- Buoyancy in diving birds
- Shock absorbers for divers like pelicans
- Sexually selected traits – sage grouse, prairie chickens, frigate birds
- Sound production by applying pressure on syrinx

AIR SACS USED IN MATING DISPLAYS

AVIAN CIRCULATORY SYSTEM

- The circulatory system delivers oxygen to tissues and returns carbon dioxide
- Relative to body size, birds have the largest hearts of any vertebrate
- Functions:
  - Transport food, oxygen, minerals, and hormones to cells,
  - remove carbon dioxide and other wastes,
  - regulate water content and temperature

AVIAN CIRCULATORY SYSTEM

- Similar to mammals and reptiles, birds have a 4-chambered heart with complete separation of oxygenated and deoxygenated blood
- Pulmonary circulation = Blood circulation to the lungs is separated from...
- Systemic circulation = general body circulation

AVIAN CIRCULATORY SYSTEM

- Blood returning from the body is pumped directly to the lungs by the right ventricle
- Newly oxygenated blood returns from the lungs to the left ventricle and is then pumped directly to body tissues
- A large proportion of oxygenated blood goes directly to legs for heat loss
- 10-20% of cardiac output goes to legs and brain

CIRCULATORY SYSTEMS

<table>
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<th>SPECIES</th>
<th>HEART SIZE</th>
<th>BEATS PER MINUTE</th>
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<td>HUMMINGBIRD</td>
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ACTIVE HUMMINGBIRD HEART RATE CAN HIT 1300 beats per minute!
CIRCULATORY SYSTEM

• As a general rule, heart rate increases with temperature: approximately 1-2 times increase in heart rate with every 10 degree C increase in temperature

• Diving birds can slow heart rate by 50% and reduce oxygen consumption by 90%
  – Blood flow is rationed to sensitive organs and greatly reduced to other organs and skeleton muscles
  – Substantial reduction in heart rate – bradycardia – starts within seconds of the head being submerged
  – Diving reflex triggered by water touching receptors in nares

AVIAN METABOLISM

Two primary types of metabolism:

Basal Metabolism
BMR is the rate of energy utilization by animal organs and tissues at complete rest, un-stimulated by digestion, assimilation of food, or low temperatures

Activity Metabolism
Total daily energy expenditures

AVIAN METABOLISM & BODY MASS

• Metabolism and daily energy expenditures typically increase with body size

• Total daily energy expenditures (kcal) do not increase as fast as basal metabolism, possibly because smaller birds are more active

• Flight metabolism can be 2 to 25 times higher than BMR

METABOLISM

Burning Fuel to Release Energy

AVIAN METABOLISM

• Energy is required for all life processes

• Birds must extract energy, minerals, and other nutrients from the environment via the foods they eat

• All birds have relatively high Basal Metabolic Rates
  • Passerines have the highest BMR of any vertebrate

• BMR relates directly to body mass with large birds expending less energy per gram of mass than small birds
  • Although the 8-kilogram bustard is 100 times larger than the 80-gram falcon, it expends only 30 times the energy

CHANGES IN BASAL METABOLIC RATE

• Just being awake can increase BMR by 25-80%

• Small birds in flight can increase energy expenditure 10-25 times BMR

• A comparably size mammal can only increase BMR 5-6 times

• A Greater Rhea's metabolism is 3.5 times BMR when walking 1 km / hr and increases to 14 times BMR when trotting (10 km / hr)
INSULATION AND HEAT LOSS

- Body heat is a direct product of metabolism – the result of the inevitable inefficiency of biochemical reactions
- The rate of heat loss from a body to the atmosphere is proportional to:
  - (1) the absolute difference between body temperature ($T_b$) and environmental temperature ($T_a$)
  \[ T_b - T_a \]
  - (2) The rate of heat transfer across the surface layers

Therefore, the rate of metabolic heat production ($H$) must balance the rate of loss to the atmosphere

Following this equation:

\[ H = \frac{(T_A - T_B)}{I}, \]

Heat = (Ambient Temp. – Body Temp) / Insulation coefficient

Insulation coefficient is resistance to heat flow

A bird’s thermal relationship with the environment becomes a complex function of the intensity of radiation and convection

INSULATION

- Feathers are the best known natural insulator and there is a direct relationship between amount of plumage and metabolic rates
- Experimental chickens with ruffled feathers that provide limited insulation have twice the BMR as normal chickens
- House sparrows will increase plumage weight by 70% in September after breeding season molt
- Arctic finches have dense down feather while tropical species do not

A Major Challenge to Survival

Maintaining high core body temperature against warmer and cooler ambient temperatures as an endotherm

TEMPERATURE REGULATION

Metabolism and Ambient Temperature ($T_a$)

Bird’s $T_b$ usually > $T_a$ so tendency is

If $T_b \geq T_{th}$, bird must shed heat against the gradient so $T_b$ does not get too high

In the thermoneutral zone, the amount of oxygen consumed by resting birds does not change with temperature

Thermoneutral zone – Range of $T_a$ over which no notable change in metabolic rate occurs to regulate $T_b$

No extra energy costs to maintain $T_b$
TEMPERATURE REGULATION

- As $T_a$ decreases, $T_b - T_a$ gradient becomes steeper.
- At some $T_a$ (lower critical temp.), metabolism increases to generate heat and reduce loss thereby keeping $T_b$ stable.
- Metabolic rate increases below the lower critical temperature (LCT) due to heat production (shivering).
- Metabolic rate increases above the upper critical temperature (UCT) due to active heat loss (panting, evaporative cooling).

RESPONSES TO COLD STRESS

- First response to cold stress is to tense muscles and shiver, which increases oxygen consumption and metabolism, therefore producing heat.
- The large pectoralis muscles are the primary heat producers supplemented by leg muscles in some species.
- Lower critical temperatures of large birds are lower than those of small birds.
  - Therefore, small birds are more sensitive to cold temps.
  - Small birds start to shiver at higher temperatures.

RESPONSES TO COLD STRESS

- Behavior plays an important role in response to temperature variation:
  - Roosting in holes
  - Burrowing in snow
  - Huddling with conspecifics
- Because much heat is lost through non-feathered legs, a chicken can reduce heat loss by up to 50% by sitting versus standing.
- By tucking the bill into shoulder feathers, another 12% reduction in heat loss can be attained.

RESPONSES TO COLD STRESS

- Physiological adaptations also play an important role:
  - At the base of the leg, in the tibiotarsal region, there is a network of veins and arteries called RETE MIRABILE (miracle network).
  - Warm, outflowing blood in the arteries is brought into close proximity with the colder venous blood returning from the lower leg.
- Thus, a bird can reduce blood flow to the extremities wherein the blood temperature might be 41 degrees in the body versus 32 degrees in the lower tibiotarsus area, to 3 degrees in the toes.
HYPOTHERMIA AND TORPOR

• At night, birds can drop their body temperatures 2-3 degrees centigrade
• This condition, where body temperature drops below normal is HYPOTHERMIA
• EXAMPLE: Black-capped chickadees and other northern titmice lower their body temperature a much as 8-12 degrees at night during extreme cold

HYPOTHERMIA AND TORPOR

• Small birds like hummingbirds can lower their body temperatures even further and enter a state of profound hypothermia call TORPOR
• During torpor they are unresponsive to normal stimuli and incapable of normal activity

RESPONSES TO HEAT STRESS

• The air temperature above which birds expend energy to dissipate heat is the Upper Critical Temperature
• Metabolism also increases due to panting, which increases evaporative cooling from the upper respiratory tract – primarily through the air sacs
• Evaporative cooling is very effective and can dissipate 100-200% of heat production
• But there is a substantial risk of water loss and dehydration

RESPONSES TO HEAT STRESS

• Birds respond to high temperatures via altering behavior, physiological change, and controlled elevation of body temperature, a condition called HYPERTHERMIA
• Heat avoidance behavior included reduced activity at midday, seeking shade, bathing, thermal soaring to areas of lower temperature

RESPONSES TO HEAT STRESS

• Desert-adapted species tend to have low metabolic rates, which reduce rates of water turnover
• Desert birds are also adapted to dissipate heat
• For example: the poorwill at 47 degree C can dissipate up to 5 times its metabolic heat production
RESPONSES TO HEAT STRESS

- Birds supplement panting by rapidly vibrating the hyoid muscles and bones in the throat – called GULAR FLUTTERING
- Gular fluttering increases heat loss via evaporation of water from the mouth lining and upper throat – very common in seabirds (think of the pelican)
- EXAMPLE: The domestic chicken may pant 300 times per minute
- Some goatsuckers pant up to 550-690 times per minute

- Because water has high capacity to absorb heat, water will cool a bird's feet more than 4 times as rapidly as air of the same temperature
- At high temperatures, a variety of storks, cormorants, ibises, and vultures take advantage of this and cool themselves by excreting on their feet

ENERGY CONSERVATION - ROOSTING SITE

- Birds can also alter energy consumption behaviorally
- Birds roosting in open habitats at night are exposed to rapid radiation of heat to sky
- Roosting with others can substantially limit this heat loss
- Example = Social Weaver of Africa
  - Social weavers cooperate to build massive colonial nest that can reach 20 feet across and hold more than 200 adults
  - As ambient air temps fall from 60 degrees to near zero, an occupied chamber remains at 60 degrees
  - To burn those extra calories a weaver would have to catch 4,500 more insects each day

THE SOCIAL WEAVER

LOCATION AND SIZE - KIDNEYS

- Located behind the lungs in a depression against the sacral vertebrae
- Because avian metabolism is so rapid, their kidneys are nearly twice the size of comparable mammals
- There is no urinary bladder in most birds (except rheas and ostriches) likely an adaptation for flight

Excretion

- Excretion of water and nitrogenous waste combines processing by kidneys, intestines, and salt-secreting glands
- Avian kidneys differ in structure and function from those of reptiles and mammals
  - Urine produced by kidney mixes with feces in small intestine where additional water can be absorbed
EXCRETORY SYSTEM

- The turnover of body tissue (about 4%/day) in birds produces toxic nitrogenous wastes
- Mammals secrete these wastes as UREA in an aqueous solution that requires large amounts of water to flush the system
- Birds secrete URIC ACID, which can be secreted as semi-solid suspension where 1 molecule of uric acid removes twice the nitrogen as 1 molecule of urea
- Birds use only 1.5-3.0 ml of water to excrete 1 gram of nitrogen as a uric acid whereas mammals would need 60 ml to do the same job

Excretion - salt

Avian kidneys can concentrate nitrogenous waste but not salt due to shorter Loops of Henle compared to mammals

Salt must be excreted via nasal salt glands
- Glands extract salt from blood and secrete it through nose as droplets of water or salt crystals
- Individuals living near salt water have larger glands

Excretion

- Excretion of nitrogenous waste in form of white uric acid crystals is unique avian adaptation
- Allows ridding of N w/ little loss of water
- Therefore birds require less water intake than mammals
- Weight reduction advantage

Summary

The daily activities of birds integrate metabolism, thermoregulation, and water economy

Time spent during different activities determines daily energy expenditure

Birds have extremely high metabolism, and both circulation and respiration have evolved to deliver and remove large amounts of fuel and waste

Birds have adapted unique physiological attributes to cope with energy and temperature demands

regulation of body temp. w/ plumage and gular fluttering

regulation of blood flow through feet

lower body temp. and enter state of torpor

behavioral adaptations