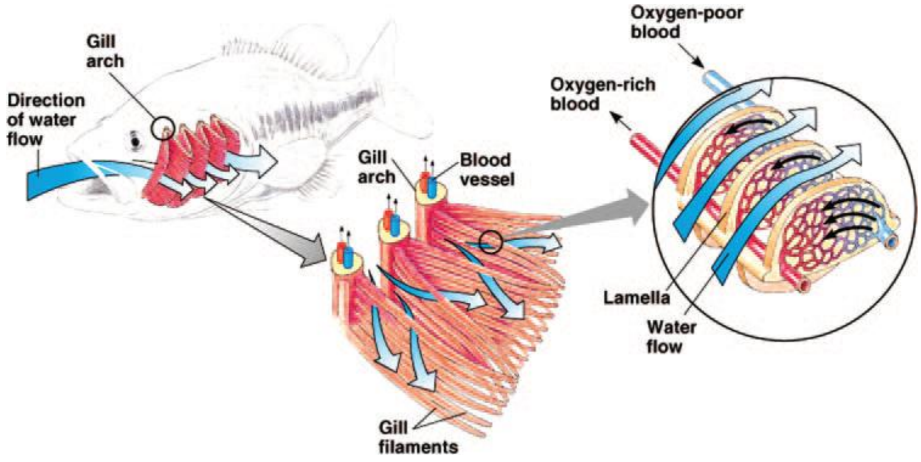
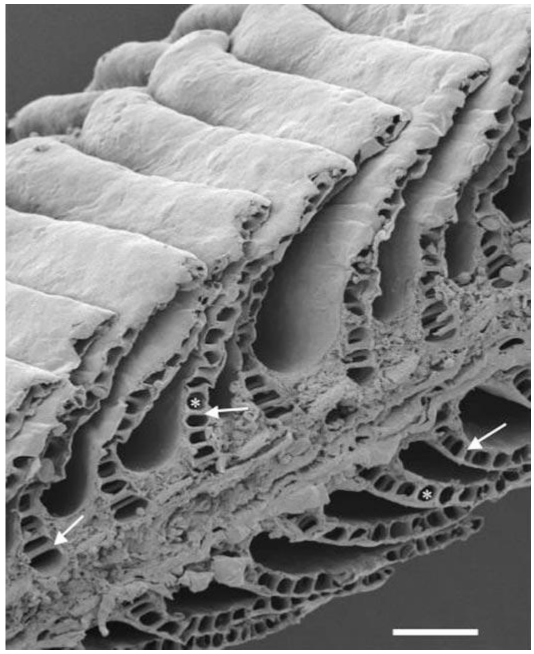
Gills

- Diagram the blood flow
- Name some of the gill functions?





Fish Cardiovascular system

- Branchial Heart – <u>4 chambers (different counting)</u>
  - Sinus venosus, atrium, ventricle, and bulbus arteriousus/conus arteriosus
- Sinus venosus has pacemaker tissues to initiate heart beat
- Atrial contraction fills ventricle
- Ventricle largest and main pressure

Fish Cardiovascular system

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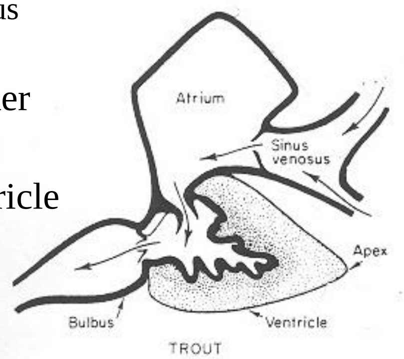


All blood goes to gills!

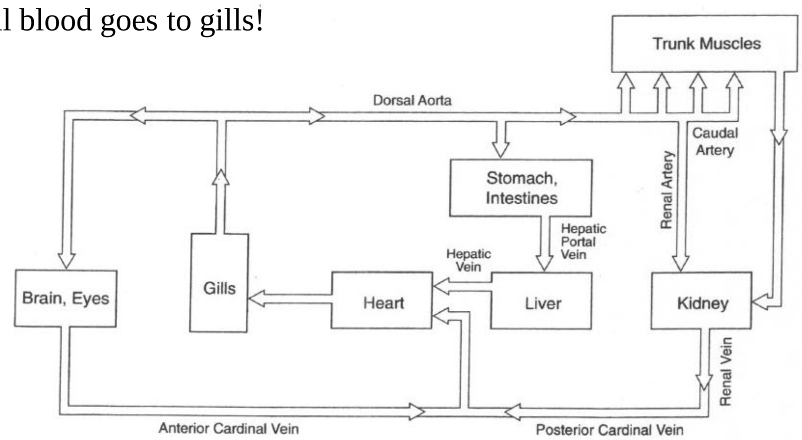


Figure 2.5. Simplified block diagram showing the major features of the fish circulatory system. Organs and tissues further from the heart must function with progressively less oxygen. Note the separate circulation of freshly oxygenated blood from the gills to the brain and return.

Adaptive Radiation

- Differences in blood pressures in fish lineages
- Highest in active teleosts

- Cardiac output (Q) is distributed to respiratory circulation via afferent branchial arteries – does not return to heart

Regulation of Q- Cardiac Output

- Changes in heart rate (Fh) and stroke volume (SVh) that are controlled by intrinsic neural and humoral control mechanisms
- Cardiac cycle is a coordinated event with contraction /relaxation cycles of atrium or ventricle separated into systolic (raised blood pressure from contraction) and diastolic periods (relaxed ejection phase)

Activity and Temperature

- Fish that have high levels activity have higher resting than sluggish forms
- Temperature has profound effect on Q and increases with temperature.

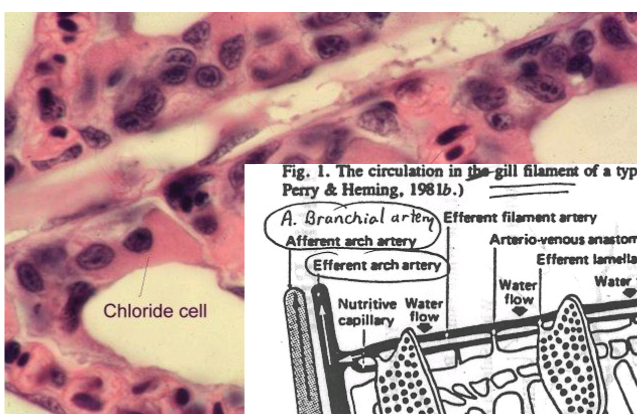
TABLE 4
Myocardial Power Output in Selected Fishes at Rest and While Swimming

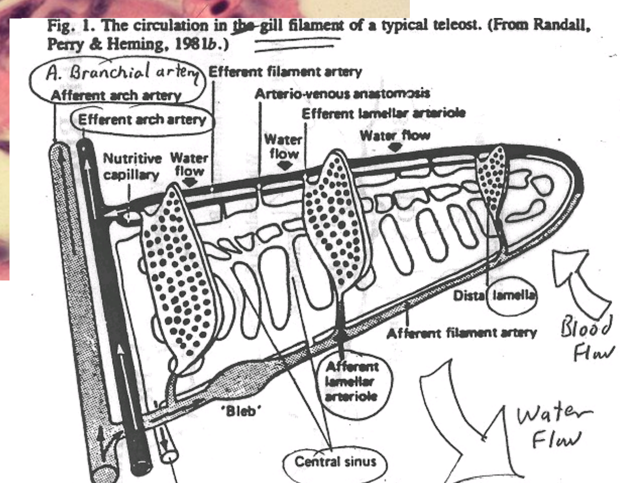
		Power output (mW/g)		Temperature	Body Mass	
		Rest	Exercise	(°C)	(kg)	Source
	Temperate-water fishes					
hagfish	*Myxine glutinosa*+	0.08	0.27	11	0.08	a
houndshark	*Triakis semifasciata*	1.71	3.30	14–24	1.93	b
Cat shark	*Scyliorhinus stellaris*	1.43	2.46	19	2.6	c
	Gadus morhua	1.77	3.29	10.5	0.4–0.8	d
lingcod	*Ophiodon elongatus*	1.18	3.21	10	4.2	e
Sea raven	*Hemitripterus americanus*	1.16	3.13	10	1.2	f
	Anguilla australis	1.08	2.19	16–20	0.9–1.1	g
	Oncorhynchus mykiss	1.53	7.03	11	1.0	h
	Oncorhynchus kisutch	1.22	5.97	5	1.4	i
	Tropical fishes					
Skipjack tuna	*Katsuwanus pelamis*	4.70	—	26	1–2	j
	Thunnus albacares	5.60	—	26	1–2	j
	Antarctic fishes					
Black fin	*Chaenocephalus aceratus*	0.98	—	0.5–2	1.0	k
crocodile	*Chionodraco hamatus**	—	1.6–3.4	0–2	0.29–0.47	l
Cod ice fish	*Pagothenia borkgrevinki*	1.05	2.00	0	0.06	m

Note: Where ventricle mass is not known values of 0.2 g/kg body and 0.08 g/kg body were assumed for elasmobranch and teleost species. Plus (+) denotes maximum value for postadrenaline infusion. Asterisk (*) denotes maximum value in a perfused heart preparation.

Blood pressures

- Systemic dorsal aortic pressure is 1/3 lower than that of ventral aortic circulation
- Primary = ventral and dorsal aortas
- secondary systems drain the veins and have accessory hearts arise from gills and arterial vessels =





Blood pressures of rainbow trout mm Hg

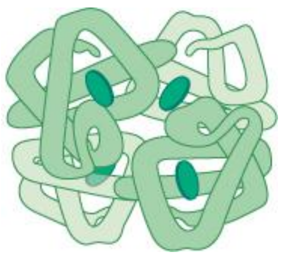
	Resting	**exercise**
• Ventral aorta	40/30	55/43
• Dorsal aorta	30/25	33/29
• Large veins	0-10	0-18

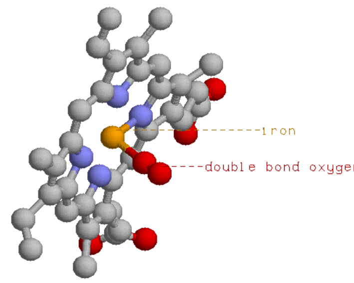
Regulation of Cardiac Activity

- Pacemaker cells – temperature response
- Autonomic neural control – neurotransmitters and Vagus activity
- Humoral control – circulating catechlomines e.g. Adrenaline and noradrenaline several types of receptors

Hemoglobin, the Magic Molecule

- Tetrameric molecule in most fish
- Two alpha two beta chains





Four disks = where the oxygen molecules bind
four sausage shapes represent polypeptide chains

$Hb + 4O_2 = Hb.4O_2$

- O2 binds to the four heme groups
- H+ and CO2 bind to specific amino acid residues in globin chain

Red Blood Cells of Fish

- Nucleated retain most organelles
- Long lived – rbt ~ 6 mo

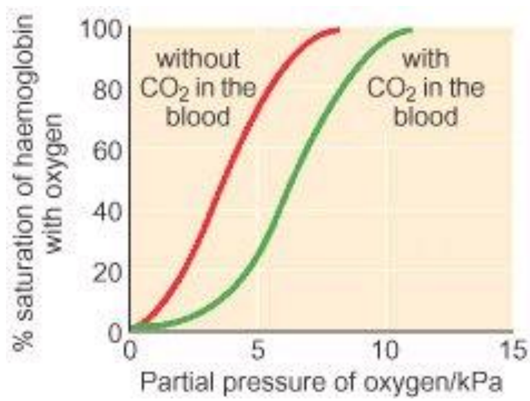
- Mammalian red blood cells biconcave and extrude their organelles shortly after release into the circulation –short lived ~ 6 days

Binding and pH

- Hb-O2 binding affinity is decreased by reduction in pH **(Bohr effect)**
- Increase in Hb-O2 saturation is associated with release of protons, termed Bohr protons, from hemoglobin (the Haldane effect)
- Acidification of rbc interior associated with CO2 to blood in tissues will augment O2 unloading in tissues via Bohr effect

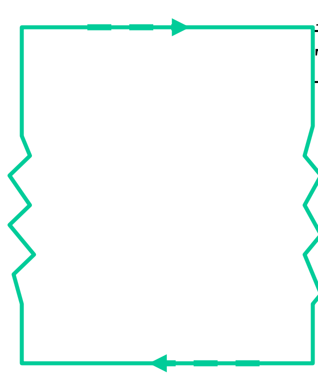
CO2diffuses into the blood plasma and RBC (erythrocytes) in the presence of the catalyst carbonic anhydrase (CA) most CO2 reacts with water in the erythrocytes and the dynamic equilibrium is established

$H_2O + CO_2 \rightleftharpoons H_2CO_3$ $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$



What the Bohr Effect Does

blood circulation



Gills outside

pH higher

pCO_2 lower

no lactic acid

Plasma and Tissues

pH lower

pCO_2 higher

lactic acid

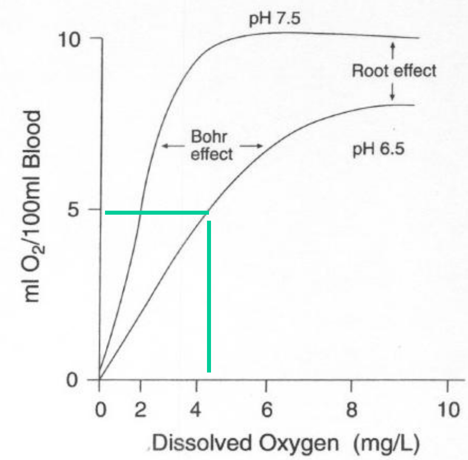
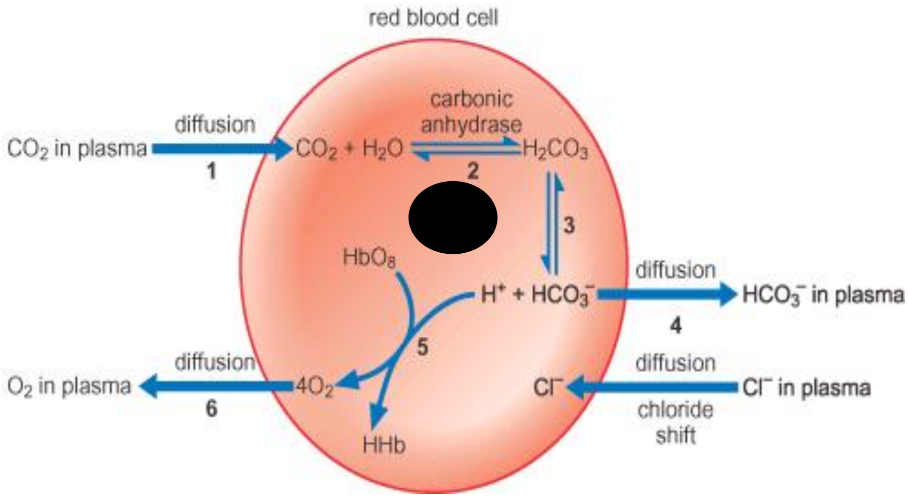


Figure 2.1. Effect of decreased blood pH due to hypercapnia or hyperlacticemia on the O_2 carrying capacity of salmonid hemoglobin.

Binding of Hb-O2

- Nucleoside triphosphates for energy
  - ATP (adenoside triphosphate) & GTP (guanosine tripohosphate)
- H ions
  - *Bohr effect*, reduction in pH decreases affinity
  - Increase in pH increases affinity



Blood samples – which is from Arctic fish?

Summary - Quantity O2 available is affected by

- Oxygen partial pressure
- Shape of oxygen equilibrium curve
- Blood oxygen carrying capacity
- Cardiac output

Modification of Blood Oxygen Carrying Capacity

- Spleen can release rbcs
  - Hypoxia; hypercapnia, exercise
- Chronic stress can also stimulate erythropoiesis (proliferation of rbc)

Catecholamines affect RBC releases

- Chromaffin tissue areas that release
  - Post cardinal vein (head kidney)
  - Other regions of kidney

Acid Base Regulation – Chemical/physical

- Normal blood pH 7.7 – 8
- Normal intracellular 7.2 – 7.5

- Maintenance via two tiered process of internal buffering, and transfer of acid base relevant molecules between animal and water

pH of fish blood is temperature dependent

- $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$
- 8.0 at 10°C
- 7.7 at 30°C

pH and temperature

- Neutral pH is only neutral at 24°C
- Below that the ph is higher
- Above that the pH is lower --- why?

Conditions that disturb Acid Base Balance

1. Metabolic acidosis – lactic acid
2. Respiratory acidosis – high CO_2
3. Environmental hypercapnia – high CO_2
4. Environmental acidosis – mine drainages, acid rain

What is pH

- Negative log of H ion concentration!

Defense Systems/Compensations

- Buffering in blood, intercellular
  - Instantaneous
- Respiratory Tissues, intercellular and extracellular
  - Within minutes
- Kidney Excretion (marginal factor in fish)
  - Slow, hours.
  - Conserving bicarbonates

Buffering in Intracellular and Extracellular Systems

- Intracellular: Proteins and Phosphates = non bicarbonate buffers – Nbbs
- = 2/3 of body fluids

- Extracellular: Bicarbonates and Ammonias
  - Major anion Na

Metabolic Acidosis

- Lactic acid produced in tissues as consequence of extreme exercise or hypoxia. H+ ions and lactate ion diffuse into blood
- Effect on buffering system is shift <u>to left</u>

•$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$

$\uparrow$ (CO_2) $\downarrow$ (HCO_3^-) $\uparrow$ (H^+)

Compensation – metabolic acidosis

- H+ excretion and / or HCO_3^- uptake

- The bicarbonate buffer shifts this to release excess CO2

Metabolic Acidosis

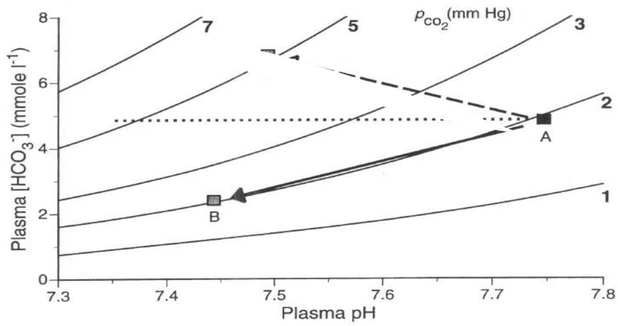


FIGURE 1. A pH-HCO_3^- diagram for a hypothetical acid-base experiment. Point "A" represents a control plasma pH of 7.75, a [HCO_3^-] of ~5.0 mmol l^{-1}, and a P_{CO_2} of 2.0 mmHg. The change to point "B" (solid arrow) demonstrates the "typical" pattern of a metabolic acidosis as plasma [HCO_3^-] decreased to 2.5 mmol l^{-1} and pH fell to 7.45. … an

Compensation

- H+ must be excreted to environment by direct or indirect exchange for environmental Na+ and/ or HCO3 – must be retained (baseline rate of exchange for environmental Cl^- must be decreased)

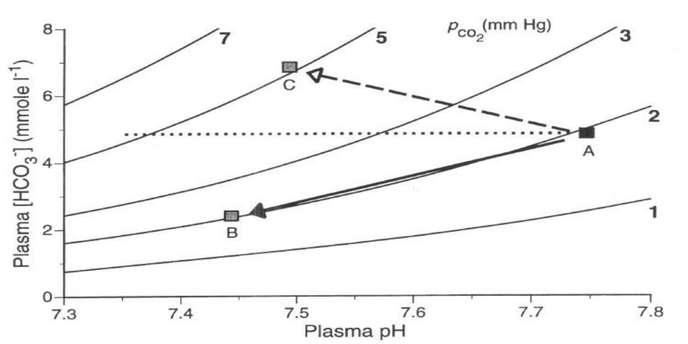
Respiratory Acidosis

- Respiratory gas CO_2 is produced in large enough quantities so that it cannot be immediately eliminated by diffusion across gills

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H$$

Respiratory Acidosis

180 *The Physiology of Fishes*



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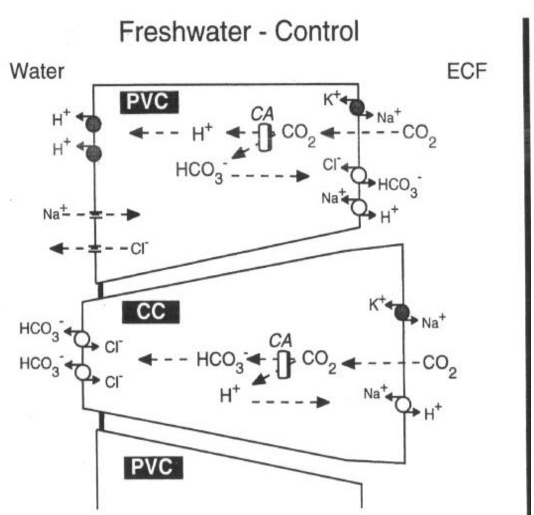
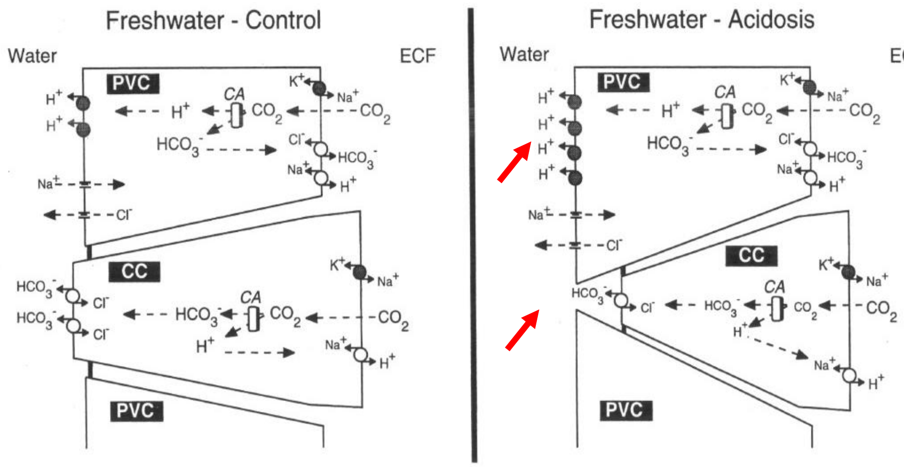
Compensation for Respiratory Acidosis

- CO_2 diffusion from blood to water will occur with bicarbonate buffering.

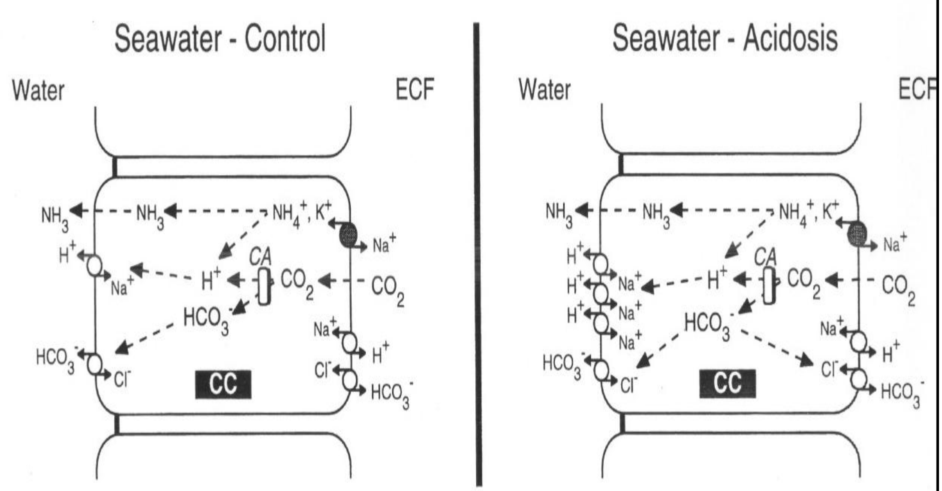
Pavement cell, chloride cells



Pavement cell, chloride cells



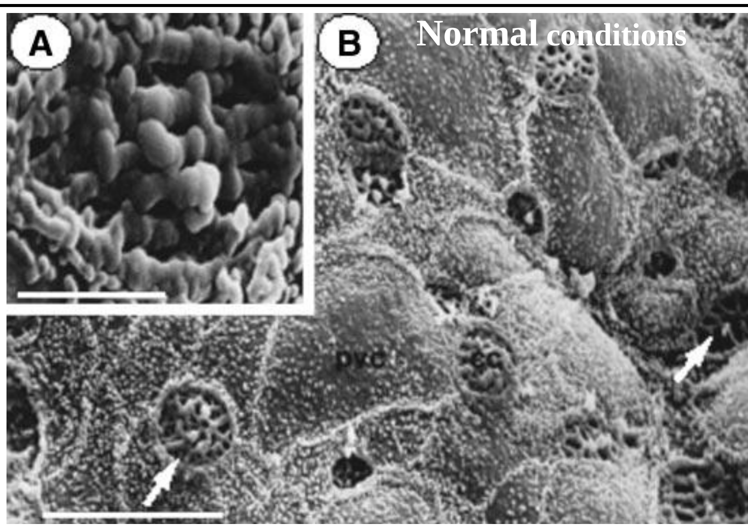
Reduction Cl increase H



Environmental Hypercapnia

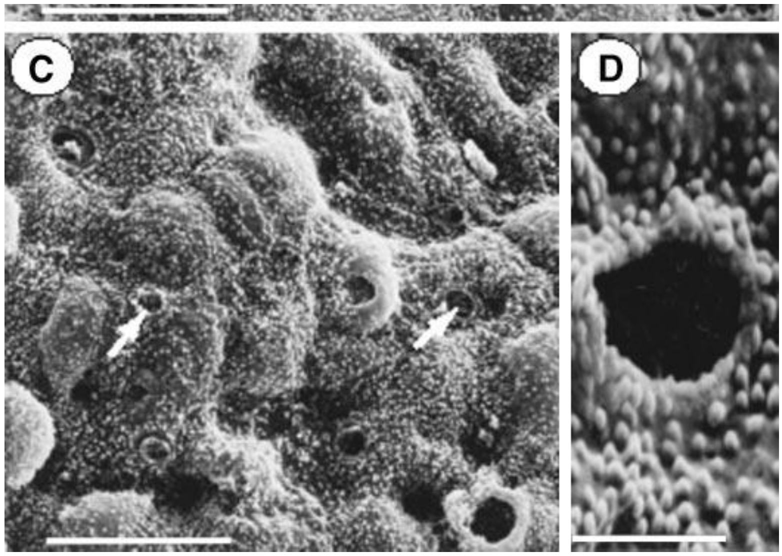
- Environmental PCO2 is elevated.
- Often by ice cover, or metabolic of plants, animals or microorganisms or *CO2 anesthesia*

$$CO2 + H2O \rightleftharpoons H2CO3 \rightleftharpoons HCO3^- + H$$

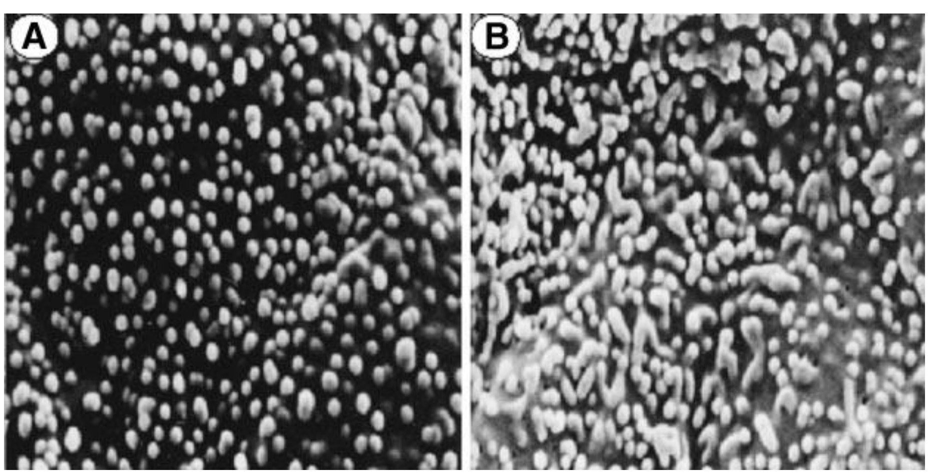


Mitochondrial rich cells (MRC- chloride cells) large area

$$CO2 + H2O \rightleftharpoons H2CO3 \rightleftharpoons HCO3^- + H$$



6 hr of hypercapnia. MRC are reduced, and look different with surface area reduced.



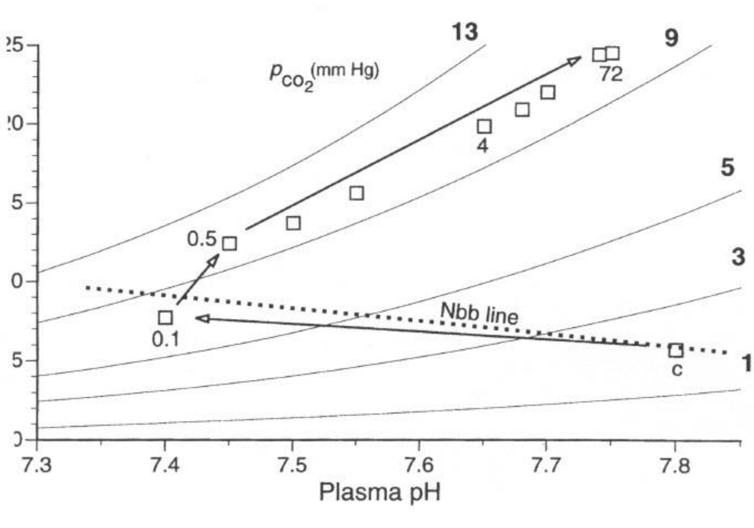
Before **After**

Epithelial pavement cells (PVC) before and after 6 h hypercapnia. Note density in microvilli is increased

Compensation

- Because environment is elevated in CO2, equilibrium is shifted, bicarbonate reserves are limited (except in air breathers)
- The compensations can take a long time, depending on the environment

Blood to water gradient is affected and excess CO2 cannot be lost by diffusion. To restore H+ back down, HCO3 must be retained, and H+ excretion increases



Environmental Acidosis

- Acidification of water due to mine drainage
- Acid rain, etc.

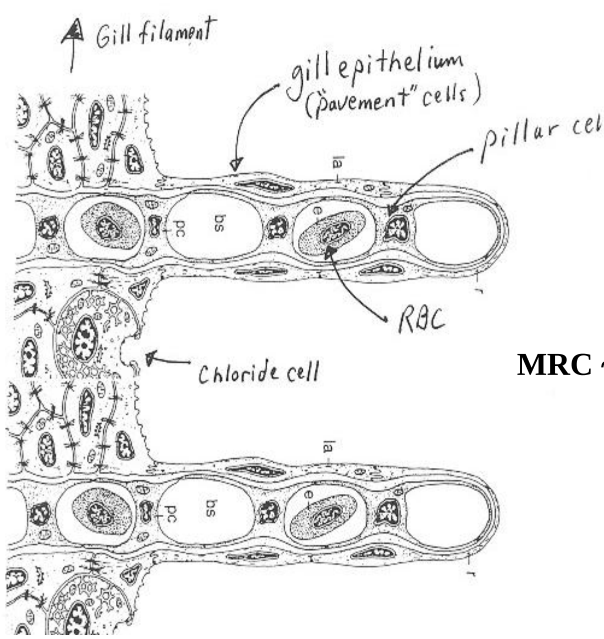
- Response similar to metabolic acidosis

Longer term compensation for acid base disturbance

- Buffering is short term
- Active exchanges occur at respiratory epithelium
- Export of H ions through Na+/H+ exchange
- Chloride cells $Cl^-/HCO3^-$ some through morphology changes

Relative contribution of bicarbonate and non bicarbonate for fixed or respiratory acid base changes for blood, and external and internal cell fractions

	Fixed Acid or Base		**Respiratory Acid Change**	
	HCO3	Nbbs	HCO3	Nbbs
Blood & Extra CF	some	some	none	all
Intra CF	little	most	none	all



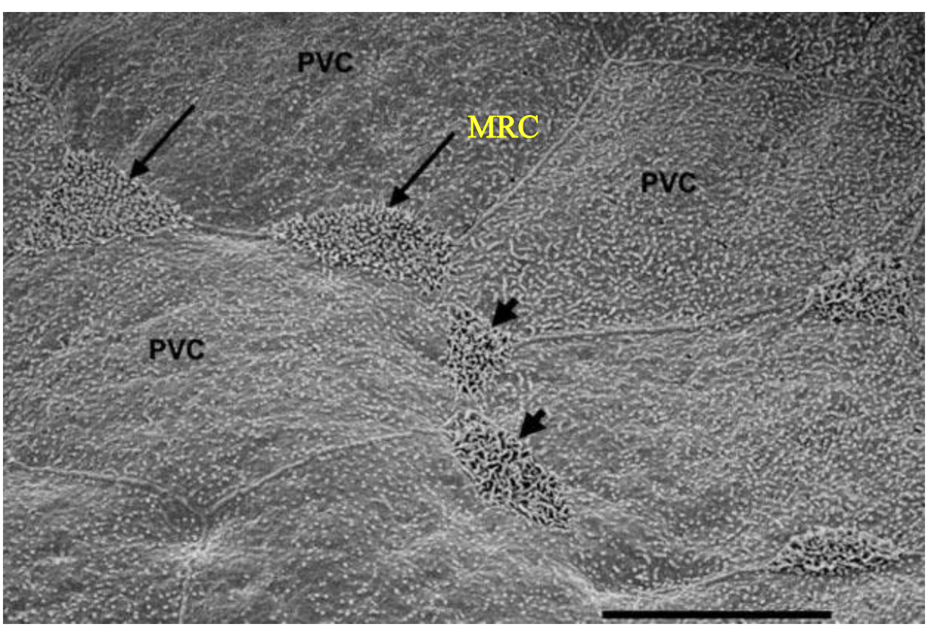
MRC ~ CC

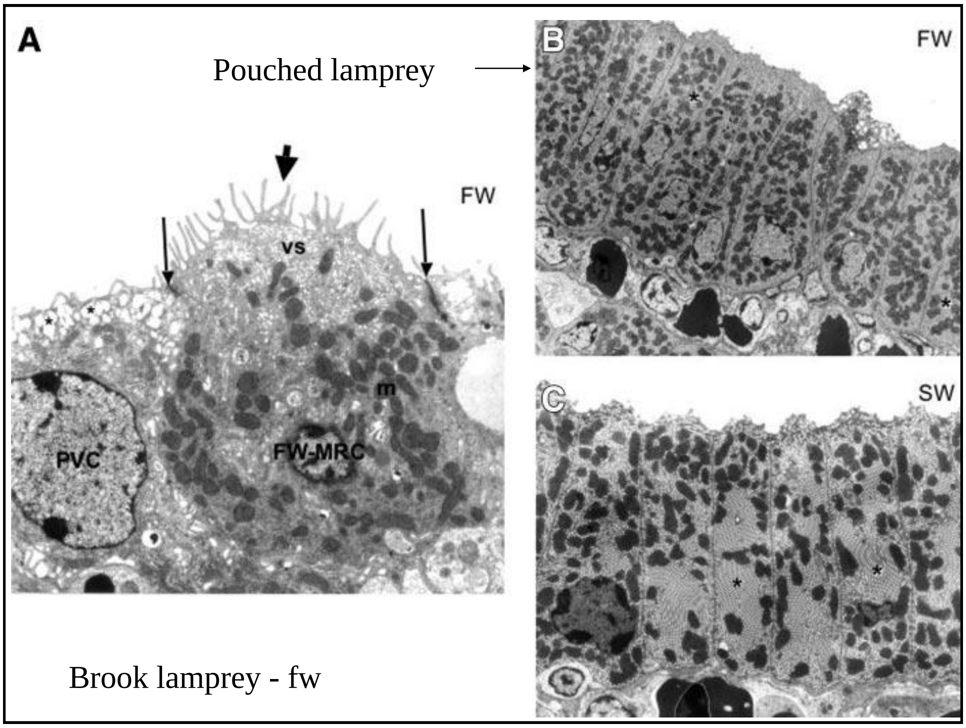
TABLE 2

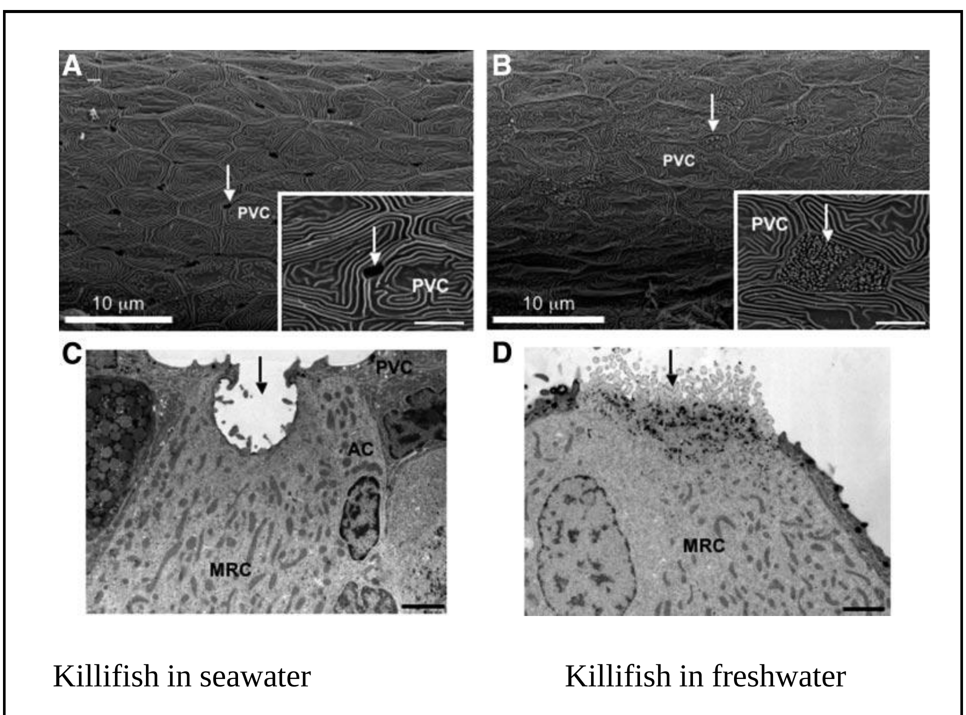
Overview of General Acid-Base Responses in Fish to External and Internal Experimental Challenges

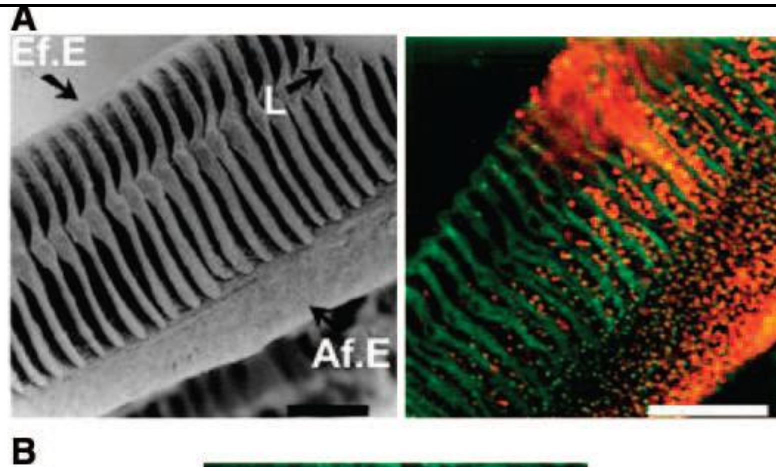
Perturbation	Acid-Base Relevant Internal Change	Extracellular Acid-Base Effect	Compensatory Response in ECF	Degree of Compensation	Fish ↔ Water Compensatory Transfers
Water hypercapnia	Hypercapnia	pH decrease	Increase plasma [HCO_3^-]	Good	Net H^+ excretion
Water hyperoxia	Hypercapnia	pH decrease	Increase plasma [HCO_3^-]	Excellent	Net H^+ excretion
Water hypoxia	Hypercapnia, metabolic acidosis	pH decrease, plasma lactate increase	Reduce P_{CO_2}, increase plasma [HCO_3^-], metabolize lactate	Excellent	Initial net H^+ excretion, later HCO_3^- excretion
Water acidification	Metabolic acidosis, gill permeability increase	pH decrease, ion loss	Decreased gill permeability (some species)	Poor to excellent	Little
Water alkalinization	Hypocapnia, metabolic alkalosis	pH increase, plasma P_{NH_3}/NH_4^+ increase	Decrease plasma [HCO_3^-], increase lactic acid	Fair to excellent	Increased ammonia excretion, urea excretion, H^+ uptake
Switch from water to air breathing	Hypercapnia	pH decrease	Increase plasma [HCO_3^-]	Poor	—
Water temperature increase	Temperature increase	pH decrease, P_{CO_2} increase, plasma [HCO_3^-] decrease	—	Little	Net HCO_3^- excretion
Exercise	Hypercapnia, metabolic acidosis	pH decrease, plasma lactate increase	Reduce P_{CO_2}, increase plasma HCO_3^-, metabolize lactate	Excellent	Initial net H^+ excretion, later HCO_3^- excretion
Acid infusion	Metabolic acidosis	pH decrease	Recovery of plasma [HCO_3^-]	Excellent	Net H^+ excretion
Base infusion	Metabolic alkalosis	pH increase	Reduction of plasma [HCO_3^-]	Excellent	Net HCO_3^- excretion

freshwater elasmobranch




A
Pouched lamprey
B
FW
vs
FW
m
PVC
FW-MRC
C
SW
Brook lamprey - fw


A
PVC
PVC
10 µm
B
PVC
PVC
10 µm
C
PVC
AC
MRC
D
MRC
Killifish in seawater
Killifish in freshwater



Gill filaments, *A*: scanning electron micrograph (*left*) and a corresponding confocal laser scanning micrograph (*right*) of a filament from a tilapia. MRCs are stained red; note their increased abundance between the lamellae, which are stained green, and on the Afferent A, compared with the Efferent A.

Autonomic nervous system mediators

	parasympathetic	sympathetic
Mediator	Acetylcholine	Epinepherine (Adrenaline and norpinepherine)
Sources	Vagus nerve	Spinal nerves Chromaffin tissue
Types of receptors	one	A receptor B receptor (dialator)

Target tissues

- Heart: Decreased or increased heart rate and stroke
- Gills: Increased or decreased resistance
- Vasculature: Increased resistance