Chemical and Biological Effects on Fishes in a High CO$_2$ World

A. Ishimatsu, M. Hayashi, K. -S. Lee (Marine Research Institute, Nagasaki University)
T. Kikkawa (Marine Ecology Research Laboratory)
J. Kita (Research Institute of Innovative Technology for the Earth)
Comparison of body fluid $PCO_2$ in air- and water-breathers

<table>
<thead>
<tr>
<th></th>
<th>$O_2$</th>
<th>$CO_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>54.7</td>
<td>54.7</td>
</tr>
<tr>
<td>Sea water</td>
<td>1.5</td>
<td>43.7</td>
</tr>
</tbody>
</table>

Solubility ($\mu M$/torr) at 20 C

Arterial Blood $PCO_2$
- Air-breathers* 15 - 40 torr
- Water-breathers 1 – 4 torr

$PCO_2$ of air/water 0.2 torr
CO₂ reactions and buffering in animal body

\[
\text{CO}_2 \xrightarrow{\text{CA}} \text{H}_2\text{CO}_3 \xrightarrow{} \text{H}^+ + \text{HCO}_3^- \xrightarrow{} \text{HCO}_3^- \xrightarrow{} \text{H}^+ + \text{CO}_3^{2-} \xrightarrow{} \text{H}^+ + \text{B}^- \xrightarrow{} \text{HB}
\]

Auerbach et al. 1997
## Osmo- and Iono-regulation in Seawater and Freshwater Fish

### Seawater Fish

- **Blood**
  - Osmolarity: 330 mOsm/L
  - Na\(^+\): 200 mmol/L
  - Cl\(^-\): 160 mmol/L

- **Drink SW**
  - Sea water
    - Osmolarity: 1,000 mOsm/L
    - Na\(^+\): 460 mmol/L
    - Cl\(^-\): 550 mmol/L

- **Excrete NaCl (Chloride cell)**

### Freshwater Fish

- **Blood**
  - Osmolarity: 300 mOsm/L
  - Na\(^+\): 150 mmol/L
  - Cl\(^-\): 120 mmol/L

- **Take up NaCl**
  - Fresh water
    - Osmolarity: 1 mOsm/L
    - Na\(^+\): 0.08 mmol/L
    - Cl\(^-\): 0.05 mmol/L

- **Large volume of urine**

### Active transport

### Passive transport
Differences in Biological Effects of CO\textsubscript{2} and H\textsuperscript{+} in Water

Effects of CO\textsubscript{2} Ocean Sequestration on Fishes
Comparison of fish mortality by CO$_2$ and acid exposures

Lethal effect of CO$_2$ and acid on embryos (N = 5) and larvae (N = 3) of silver seabream at two pH conditions. Exposure period: embryo 360 min, larva 24 h

*Significant difference between groups.

Acid-base responses to CO$_2$ and acid seawater in bastard halibut, *Paralichthys olivaceus*

Seawater was acidified by either bubbling with 5% CO$_2$ in air (○) or adding sulphuric acid (●) to same pH of 6.2.

$$pH = pK' + \log \frac{[\text{HCO}_3^-]}{\alpha \times P\text{CO}_2}$$
Effects of high CO$_2$ plasma ions and chloride cells of marine fishes

Gill chloride cells in bastard halibut

$P$CO$_2$ 37 torr Initial

Japanese amberjack

$P$CO$_2$ 7 torr

$P$CO$_2$ 22 torr

Gill chloride cells in bastard halibut

$P$CO$_2$ 37 torr Initial

24 hr
Effects of high CO$_2$ on ion fluxes of freshwater rainbow trout

Hypercapnia

- Efflux (Blood to water)
- Influx (Water to blood)

Kidney

Gills

Hyperoxia-induced hypercapnia. Wood et al. (1984)
Effect of acid water on ion fluxes of freshwater rainbow trout

Unidirectional influx

Unidirectional efflux

Net flux

[Ca$^{2+}$] 0.24 mEq/L, McDonald et al. 1983
Differences in Biological Effects of CO₂ and H⁺

- Physiological responses to CO₂ and acids are different.
- CO₂ readily diffuses into the body, and acidifies body fluid of both intracellular and extracellular compartments. Fish kill mechanism by high CO₂ is not fully understood.
- Acid exposure inhibits active ion transports across the gills, and increased passive ion movements. The main cause of fish kill by acid exposure is thought not to be blood acidification but cardiac failure by hemoconcentration.
Differences in Biological Effects of CO₂ and H⁺ in Water

Effects of CO₂ Ocean Sequestration on Fishes
CO₂ sequestration by the moving-ship method

Depth ca. 2,000-2,500 m
Temperature ca. 2-3 °C

Initial exposure to high CO₂ levels followed by rapid decreases in CO₂.

Sato and Sato 2002
Effects of CO₂ on cardiovascular system of amberjack

Cardiac output (ml/min/kg)

Heart Rate (beats/min)

Blood Pressure (cmH₂O)

Time (h)

Cardiac output (ml/min/kg)

Blood pressure (cmH₂O)

Time (min)
Fish mortality by unsteady exposures to CO₂

Effect of step-increase CO₂ exposures on fish mortality: Japanese sillago
1 kPa = 7.5 torr

- No mortality after pre-exposure to 1 kPa
- Sudden drop of $PCO_2$ quickly killed the fish.
- Ca. 100% mortality at 5 kPa
Experiments on deep-sea fish under high pressures

High Pressure Chamber (Max 50 MPa)

Careproctus trachysoma: Liparididae

Known distribution depth 400-800 m
Water temperature 2°C
Summary

- When tested at the same pH, CO₂ and acids produce different effects on fish. Data on mineral acids cannot be used to evaluate effects of CO₂.

- Still, useful information may be obtained from the literature on the effects of water acidification on fishes, which has already made great impacts on freshwater ecosystems.

- Fish kill mechanism by lethal levels of CO₂ must be clarified, particularly focusing on the role of cardiac response.

- Effects of ocean sequestration need to be investigated; on deep-sea animals, under high pressures, at low temperatures, and in unsteady CO₂ conditions.

- Long-term effects at sublethal CO₂ levels on fishes should also be investigated.
CO₂ reception in fish

Eel palatine CO₂ receptors

pH of the test solution was 5.0
Test solution acidified by HCl to pH 5.0 gave no response.

Yoshii et al. (1980)
Effects of long-term CO₂ exposure on growth of Japanese sillago

Low  3 torr
Mid   5 torr
Hi     9 torr

WT 25 C
34 psu
Alkalinity 2.3 mEq/L
1 atm
Changes in arterial pH and mortality during hypercapnia in bastard halibut

**pH**

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>24</th>
<th>48</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survival rate (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

PCO₂:
- 7 torr
- 22 torr
- 37 torr
### Effect of long-term CO₂ exposure on fish growth

<table>
<thead>
<tr>
<th>Species</th>
<th>%BW of Cont</th>
<th>PCO₂ (torr)</th>
<th>Temp (°C)</th>
<th>Duration (days)</th>
<th>Water pH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seawater</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td>63</td>
<td>20</td>
<td>15-16</td>
<td>43</td>
<td>6.4</td>
</tr>
<tr>
<td>Spotted wolffish</td>
<td>64</td>
<td>20</td>
<td>6</td>
<td>70</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Fresh water</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainbow trout*</td>
<td>52</td>
<td>17</td>
<td>9</td>
<td>275</td>
<td>6.2-6.3</td>
</tr>
<tr>
<td>Rainbow trout**</td>
<td>76</td>
<td>17</td>
<td>9</td>
<td>275</td>
<td>6.2-6.3</td>
</tr>
<tr>
<td>White sturgeon</td>
<td>62</td>
<td>20</td>
<td>19</td>
<td>28</td>
<td>7.0</td>
</tr>
</tbody>
</table>

*Fed normal mineral diet, **Fed low mineral diet

**H⁺ Exposure**

- Branchial Ion Loss
  - Extracellular to Intracellular Fluid Shift
  - Reduced Plasma Volume
    - Adrenergic stimulation
      - Cardiac Failure?
      - Increased Blood Viscosity
      - Increased Blood Pressure
  - Red Blood Cell Swelling

**CO₂ Exposure**

- Body Fluid Acidification
  - Cardiac output Decreases
  - Blood Pressure Increases
  - Plasma Ion Imbalance
    - Cl⁻ Decreases
    - HCO₃⁻ Increases
    - Na⁺ Increases
  - pH Compensation

H⁺ inhibits ion transport at the gills surface.

CO₂ readily penetrates into the body to affect physiological functions.

Body fluid acidification may be unimportant as a direct cause of death.
Locomotor responses to CO₂ and H⁺

Avoidance threshold $PCO_2$ 2-4 torr

Arctic char (Jones et al. 1985)