Lecture 14 : Bioenergetics, big picture calcs.

- Energy consumption, measurement
- Gibbs free energy revisited.

Example Questions (Exam 2017)

37) A 65g 'power bar' developed for endurance athletes contains 4.5g of fat, 47g of carbohydrate and 8.5g of protein. The energy densities of the food constituents are as follows: fat contains 39 kJ/g, carbohydrate contains 16 kJ/g, protein contains 18 kJ/g.

a. What is the total energy content of the power bar? **(1 mark)**

Total energy of power bar: ____________

b. Jogging requires a total energy expenditure of 570 kcal/h, as measured using indirect calorimetry. Given the chemical energy provided by the energy bar above, determine how long you could jog for after eating the energy bar. One calorie = 4.184 J. **(2 marks)**

Time: ________

39) The phosphorylation of glucose is the initial step in the catabolism of glucose in the cell.

Glucose + P → glucose-6-phosphate + H_2O

$\Delta G = 13.8$ kJ/mol

a. Explain why this reaction does not take place spontaneously. **(1 mark)**

Answer:

b. In the cell, the reaction is coupled to the hydrolysis of ATP. Explain how coupling the reaction to ATP hydrolysis enables the phosphorylation of glucose to take place in the cell. **(1 mark)**

Answer:

3.3 Animal energy consumption and measurement

L14. ↓

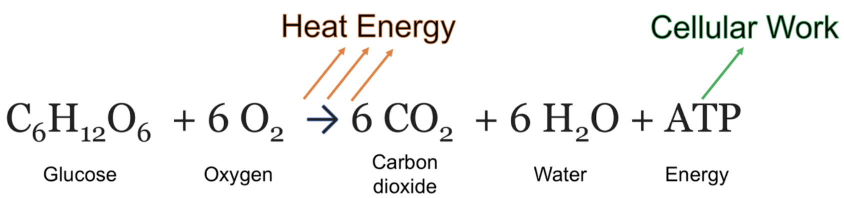
Or...**food, energy and life!**

Food content: food is primarily composed of the macromolecules:

1. Carbohydrate
2. Protein
3. Fat

(Macromolecules are 'very large' molecules, $\sim$ 1000s of atoms).

About 40% of the energy of food is converted to **cellular work**, and the rest to body heat, via **cellular respiration**. This is discussed in detail later, but illustrated below.



Cellular respiration.

See later: Food → Energy → Work

3.3.1 Measuring energy

How can we measure how much energy is required for various animal (e.g. human) activity? In particular, **we can't burn or explode people** (well, we probably shouldn't...).

Instead, we can calculate this energy *indirectly*, via so-called **indirect calorimetry**. This takes into account:

1. The *consumption* of oxygen
2. The *production* of waste (carbon dioxide and nitrogen).

For example the **Weir equation** is

$$\text{Energy Expenditure} = 1.44[3.94V_{O_2} + 1.106V_{CO_2}]$$

where V_{O_2} is the volume of oxygen consumption and V_{CO_2} is the volume of carbon dioxide consumption. This can be measured using a setup like that shown in Figure 22.

Figure 22: Indirect calorimetry. (From `https://peakzonefitness.com/product/vo2-max-test/`.)

The upshot for use is that we can measure **energy input** (food) and **energy output** (activity).

The table below gives some useful data on food inputs and activity outputs.

Example Problems 3: Energy and activity

1. A calorie is a unit of energy that is often found in older texts and is still common in food science. One calorie = 4.184 J, which is the energy required to increase the temperature of 1 g of H_2O from 14.5 °C to 15.5 °C. Using

'direct calorimetry' 'indirect calorimetry'

Substance	Energy yield			Form of Activity	Total energy expenditure ($kcal.h^{-1}$)
	$kJ.mol^{-1}$	$kJ.g^{-1}$			
Glucose	2,817	15.6		Lying still, awake	77
Lactate	1,364	15.2		Sitting at rest	100
Palmitic acid	10,040	39.2		Walking, level ground	200
Carbohydrate	-	16		Sexual intercourse	280
Fat	-	37		Biking, level ground	305
Protein	-	23		Walking, uphill	360
Ethyl alcohol	-	29		Jogging	570
Coal	-	28		Rowing	830
Oil	-	48		Maximal activity (untrained)	1440

Table 1: Heat released upon oxidation to CO_2 and H_2O and total energy expenditure during some example activities, as measured using *indirect calorimetry*. (From notes by Thor Besier.)

the tables given, calculate the total energy expenditure (in J) following 20 mins of jogging, and compare this to 2 h of walking on level ground.

2. Estimate how high a ladder could a 70kg person climb, fueled by a chocolate bar with the following nutritional content: 10g fat, 45g sugar, and 3g protein. Assume muscle is 24% efficient and obtain energy yield from the given tables. ie carb.

3. The average power output from a human labourer is 100 W. What does this equate to in terms of total energy per day (let's assume you can work for 24 hrs straight)?

4. The energy density of fat is 37 kJ/g. A 70kg human might have $\sim$ 10kg of fat. What is the total amount of energy in our bodies that can be derived from fat?

5. The energy density of a lithium-ion battery is 0.4 MJ/kg. What is the total energy that can be derived from a 10kg li-ion battery and compare this to

the equivalent energy derived from fat.

6. A 2017 model S Tesla can be purchased with a top-range 100 kWh battery. What is the total energy equivalent of this battery and how does this compare to the potential energy derived from fat from a human?

Answers

1. Jogging 20 min : $\left[\underbrace{570\times10^3 \frac{cal}{h} \times \left(\frac{4.184\,J}{1\,cal}\right) \times \left(\frac{1\,h}{60\,min}\right)}_{\text{energy/min}}\right] \times 20\,min$

$\times$ min.

$\approx \boxed{795\,kJ}$

Walking 2h : $\left[\underbrace{200\times10^3 \frac{cal}{h} \times \frac{4.184\,J}{1\,cal}}_{\text{energy/h}}\right] \times 2h$

$\times$ h

$\approx \boxed{1700\,kJ = 1.7\,MJ}$ (> Jogging 20min)

2. Energy in bar $= 10\,g \times 37 \frac{kJ}{g} + 45\,g \times 16 \frac{kJ}{g} + 3\,g \times 23 \frac{kJ}{g}$

$\approx 1159\,kJ$

equate

Energy available for work $= 0.24 \times 1159\,kJ \approx 278\,kJ$

Energy used $= mgh = 70 \times 9.81 \times h$ J

(max height) $\Rightarrow h = \frac{278\times10^3\,J}{70\times9.81\,J/m} \approx \boxed{404\,m}$

3. $100\,W = 100 \frac{J}{s} \times \left(\frac{60\times60\times24\,s}{1\,day}\right) \approx 8.64\times10^6\,J/day$

$\approx \boxed{8.6\,MJ/day}$

4. $37 \frac{kJ}{\cancel{g}} \times 10 \times 10^3 \cancel{g} = 370{,}000\ kJ$

$= \boxed{370\ MJ}$ (so $\frac{370}{8.6} \approx 43$ days of labour!)

5. $10\ kg \times 0.4 \frac{MJ}{kg} = \underline{4\ MJ} \ll$ energy from fat (but more available/convenient!)

6. $100\ kWh \rightarrow MJ$?

$$\left[100 \times 10^3 \frac{J}{s} \times h\right] \times \left(\frac{60 \times 60\,s}{1\,h}\right) \approx \boxed{360\ MJ}$$

$\approx$ same as total fat content of body.

3.4 Gibbs free energy applied to biological systems

Recall that a spontaneous process can be thought of as, loosely, a change from a 'less natural' state to a 'more natural' state. E.g. for an *isolated* system is it 'natural' to move from 'order' to 'disorder', i.e. for **entropy to increase towards a maximum.**

For **open systems** the more natural principle is for the **Gibbs free energy to decrease towards a minimum**.

both: entropy production ≥ 0

We recap some key facts below.

Gibbs free energy

Key

def^n: $G = U + PV - TS$
or $G = H - TS$, since $H = U + PV$

'Natural' direction (according to entropy production) always production ≥ 0

$dG < 0$ spontaneously.

Interp: 'maximum available non-PV, eg chemical, work at constant pressure & temperature'

chemical work

Math. not examined

• def^n: $dG = dU + PdV + VdP - TdS - SdT$
$= dU + PdV - TdS$

$\delta^e S = \frac{\delta Q}{T}$ = entropy transport

• 1st Law: $dU = \delta W^{on} + \delta Q^{in}$
• 2nd Law: $dS = \frac{\delta Q^{in}}{T} + \delta^i S$, $\delta^i S \geq 0$:

$\delta^i S \geq 0$ entropy production ('inside')

combine

1st & 2nd: $dU = \delta W^{on} + TdS - T\delta^i S$

into dG: $dG = (\delta W^{on} + \cancel{TdS} - T\delta^i S) + PdV \cancel{- TdS}$

$= \underbrace{\delta W^{on} - (-PdV)}_{} - T\delta^i S$

$\delta W^{on}_{non PV}$ = 'non PV work' (Note: +PV work on is $-PdV$)

$\Rightarrow dG = \delta W^{on}_{nonPV} - T\delta^i S$
$\delta W^{by}_{nonPV} = -\delta W^{on}_{nonPV}$

$\boxed{-dG = W^{by}_{nonPV} + T\delta^i S}$

$\boxed{W^{by}_{nonPV} \leq -dG}$, eg $dG = -30\text{kJ} \Rightarrow W^{by}_{nonPV} \leq 30\text{kJ}$

If 'leave alone' (no work), $\boxed{dG = -T\delta^i S < 0}$

naturally decreases.

($W^{by} = -W^{on}$ always)

End L14.

L15

Note: need specific mechanism! (thermo won't tell you)

3.4.1 Gibbs free energy and coupling

In a given process we need the **overall** process to be favourable. But individual steps/components can be unfavourable (when in isolation) as long as they are appropriately **coupled**. This is particularly true of *biochemical* reactions which are often highly coupled.

A chemical reaction is called **exergonic**, i.e. gives off energy, if it has $\Delta G < 0$. These are **spontaneous**.

spontan.

available for work