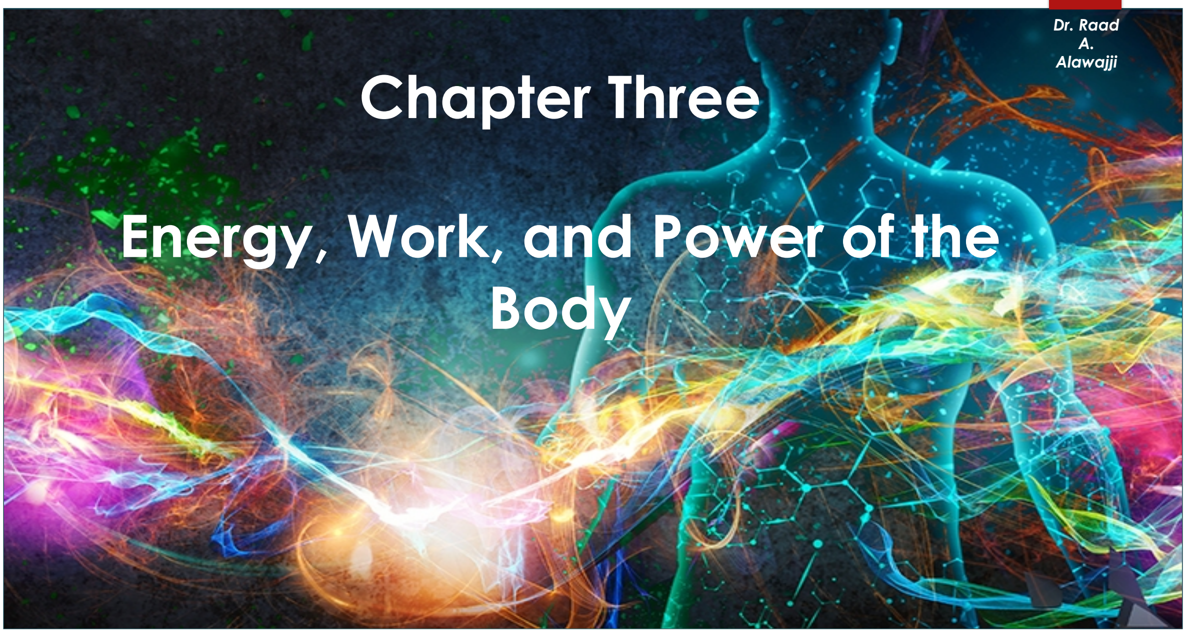
Dr. Raad A. Alawajji

Medical Physics

PHY-311

2024-2025



3-1 Introduction

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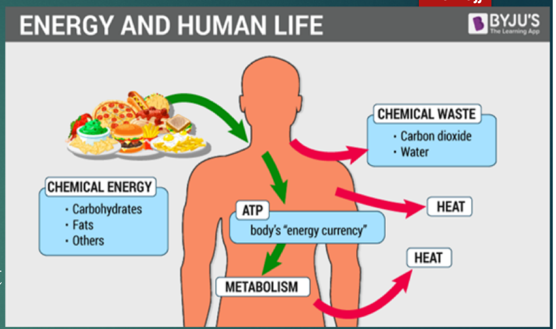
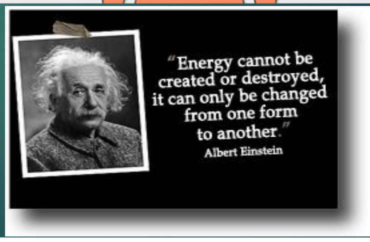
- The energy is defined as the capacity of the body to do a work.
- The study of the relationship between heat, work, and the associated flow of energy is described by thermodynamics.
- The First Law of Thermodynamics states that energy, which includes heat, is conserved.
- Second Law of Thermodynamics is that spontaneous change in nature occurs from a state of order to a state of disorder.
- Energy can neither be created nor destroyed.





3-2 Energy Conversion in Humans

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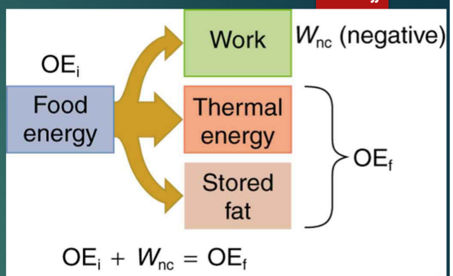
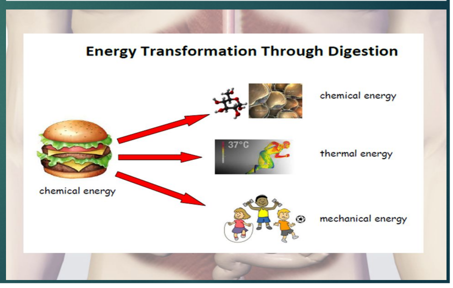
- Our own bodies, like all living organisms, are energy conversion machines.
- Conservation of energy implies that the chemical energy stored in food is converted into **work**, **thermal energy**, and/or stored as **chemical energy in fatty tissue**.
- The fraction going into each form depends both **on how much we eat** and on **our level of physical activity**.





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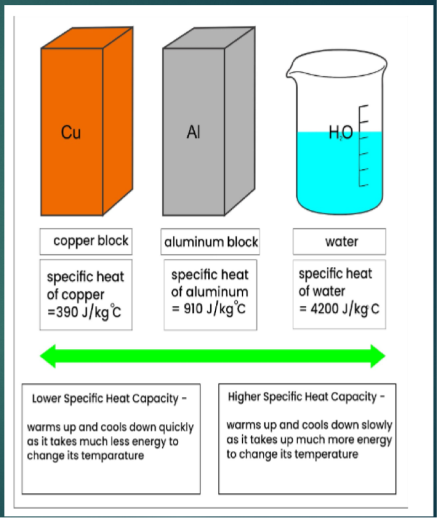
- The **Heat capacity** *C*, which is the energy (or more specifically, the heat) required to raise the temperature T of an object by $1^{\circ}C$.
- The heat capacity per unit volume or mass is the **Specific heat** *c*.
- The heat capacity is an extensive property of a given object such as (volume, mass), while the specific heat is an intensive property (density) of a material.
- The heat capacity C is the specific heat (expressed per unit mass) × the total object mass m, so $C = mc$.



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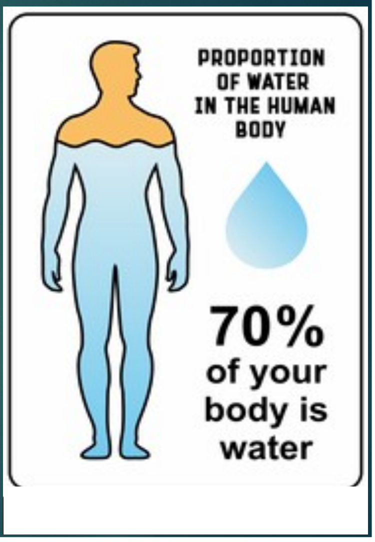
- The temperature rises ΔT of an object with a heat flow Q to the body is:

$$\Delta T = \frac{Q}{mc}$$

- For water, c_{water} = 1.0 cal/g-°C = 1.0 kcal/kg-°C. Even though the human body contains much water, the average specific heat of the body is a bit less, c_b = 0.83 cal/g-°C = 0.83 kcal/kg-°C .
- This means that it takes 83 kcal to raise the temperature of a 100 kg person by 1.0°C
- This 83 kcal (83 food calories) is around the food energy content of a slice of bread.



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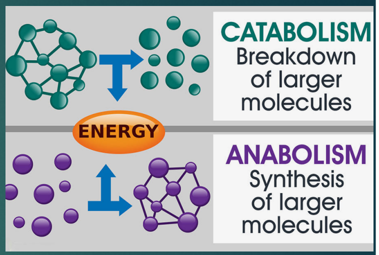
3-3 Power Consumed at Rest

- The rate at which the body uses food energy to sustain life and to do different activities is called the **metabolic rate.**
- **Metabolic rat**e processes can be divided into Catabolic and Anabolic reactions.
- **In catabolic reactions** complex molecules are broken into simple ones, for purposes such as energy usage.
- **In anabolic reactions** simple molecules are combined to form complex ones, for purposes such as energy storage
- The total energy conversion rate of a person at rest is called **basal metabolic rate BMR**



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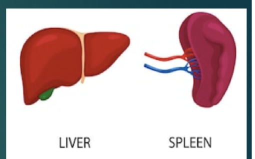
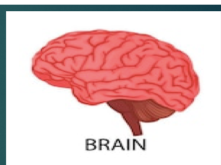
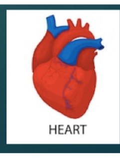
For example, a man weighing 70 kg lying quietly awake consumes about 70 Cal/h. (1 cal=4.18 J; 1,000 cal =1 Cal; 1 Cal/h=1.16W).

- The largest fraction goes to the liver and spleen, with the brain coming next during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly.
- About 75% of the calories burned in a day go into these basic functions
- The BMR is a function of **age**, **gender**, **total body weight**, and **amount of muscle mass.**
- Athletes have a greater BMR due to this last factor.







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- To obtain the total energy consumption per hour, we multiply the metabolic rate by the surface area of the person.
- The following empirical formula yields a good estimate for the surface area:

$$\boldsymbol{Area = 0.202 \times W^{0.425} \times H^{0.725}\ (m^2)}$$

W is the weight of the person kg, and H is the height of the person in m.

For instance, the surface area of a 70-kg man of height 1.55m is about 1.70 m^2 His metabolic rate at rest is therefore (40 Cal/m^2-hr)×1.70 m^2 = 68 Cal/hr, or about 70 Cal/hr

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- Energy consumption is proportional to oxygen consumption because the digestive process is basically one of oxidizing food.
- The energy of people can be measured by measuring their oxygen use.

Approximately **20 kJ** of energy are produced for each **liter of oxygen consumed**, independent of the type of food. This ratio is known as the **Caloric Oxygen Equivalent COE**

$$COE = 1L[O_2] \triangleq 20\ \frac{KJ}{[O_2]}$$

- The **kidneys** and **liver** consume a surprising amount of energy.
- The biggest surprise of all is that a full 25% of all energy consumed by the body is used to maintain electrical potentials in all living cells.

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We can confirm the COE with an examples of four main food items, which are:

1. Carbohydrates (sugar, glucose): $C_m(H_2O)_n$
2. Fat (i.e., palmitic acid): $CH_3(CH_2)_{14}COOH$
3. Proteins (i.e., alanine): CH_3–$HCNH_2$–$COOH$
4. Alcohol: $C_2H_5(OH)$

Energy density, caloric oxygen equivalent (COE)

Food item	Energy density (kJ/g)	COE (kJ/l O_2)
Carbon hydrates	15.4	20.7
Proteins	17.6 (22)	19.3
Ethanol	29.8	20.4
Fat	27–40	19.4

- We first consider the COE of 1 mol of glucose ($C_6H_{12}O_6$).
- The physical burning of 1 mole glucose (180g) with oxygen yields the reaction:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2.78\ \text{MJ/mol}_{\text{Glu}}$$ exothermic

- In contrast, the catabolic burning of glucose occurs in form of the reaction:

$$C_6H_{12}O_6 + 6O_2 + 38ADP + 38Pi \rightarrow 6CO_2 + 6H_2O + 38\ ATP + 0.956\ \text{MJ/mol}_{\text{Glu}}$$

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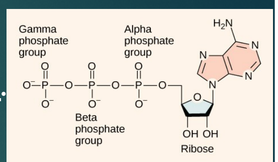
In the catabolic reaction, ATP (adenosine triphosphate) molecules as energy storage is synthesized from ADP with the phosphate group PO_4^{3-} (symbolized as Pi).



A nitrogenous base (adenine), the sugar ribose, and the triphosphate.

The energy difference is used for ***the ATP synthesis***:

$$2.78\ MJ/mol_{Glu} - 0.956\ MJ/\ mol_{Glu} = 1.824\ \text{MJ}/\ mol_{Glu}$$

Or an energy $1.824 MJ/38\ mol_{ATP}$= 48 kJ/mol $_{ATP}$, the remaining energy of 0.956MJ is available as heat.

- ATP is an energy storage molecule like a rechargeable battery used for cellular work when needed.
- The back-conversion of ATP into ADP releases −30.5 kJ/mol_{ATP} of stored energy.
- The breakdown of sugar and conversion to energy are called **cellular respiration**.

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Next, we determine the mole volumes of the reaction partners:

$22.4L\ of\ C_6H_{12}O_6,\quad 134.4\ L\ of\ O_2,\quad 134.4.\ L\ of\ CO_2\ and\ 134.4\ L\ of\ H_2O$

The molar mass of the reactants before and after the reaction is

$180\ g + 192\ g \longrightarrow 264\ g + 108\ g$

Using the oxygen mole volume, we find the COE of glucose as follows:

$$COE\ (C_6H_{12}O_6) = \frac{2.78\ MJ}{134.4\ L\ [O_2]} = 20.7\ \frac{KJ}{L\ [O_2]}$$

The energy density (ΔE) normalized by the glucose:

$$\frac{\Delta E}{m_{mol}((C_6H_{12}O_6))} = \frac{2.78\ MJ}{180\ \ g_{Glu}} = 15.4\ \frac{KJ}{g_{Glu}}$$

Thus, confirming the statement made in the beginning.

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3-4 Energy from Food

(1) Operate organs.

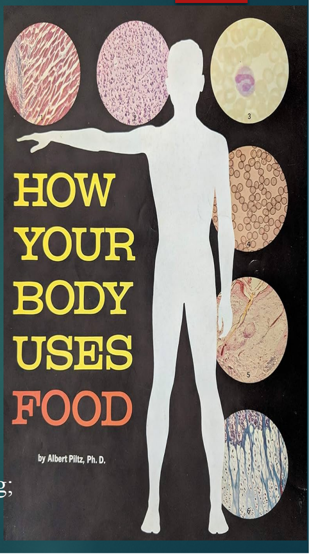
(2) Maintain a constant temperature by using some of the heat that is generated by operating the organs (while the rest is rejected).

(3) Do external work.

(4) Build a stored energy supply (fat) for later needs.

(5) Grow to adulthood, and

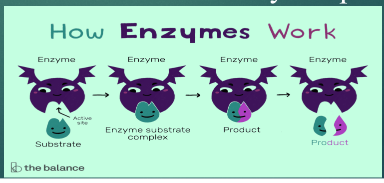
(6) Help the fetus grow during pregnancy and then nurse infants.



- For every gram of glucose ingested, 3.81 Cal of energy is released for metabolic use.
- On the average, carbohydrates (sugars and starches) and proteins provide about 4 Cal/g; lipids (fats) produce 9 Cal/g, and the oxidation of alcohol produces 7 Cal/g.

Dr. Raad A. Alawajji

- The oxidation of food, which releases energy, does not occur spontaneously at normal environmental temperatures.
- For oxidation to proceed at body temperature, a catalyst must promote the reaction.
- In living systems, complex molecules, called enzymes, provide this function.
- In the process of obtaining energy from food, oxygen is always consumed.
- It has been found that, independent of the type of food being utilized, 4.83 Cal of energy are produced for every liter of oxygen consumed.
- Knowing this relationship, one can measure with relatively simple techniques the metabolic rate for various activities.



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- Assuming, as before, that the surface area of the person whose activities are shown in the table is $1.7 m^2$, his/her total energy expenditure is 3944 Cal/day.
- If the person spent half the day sleeping and half the day resting in bed, the daily energy expenditure would be only 1530 Cal.
- The daily energy needs of the person (surface area $1.7 m^2$) whose activities are shown in table are met by the consumption of 400 g of carbohydrates, 200 g of protein, and 171 g of fat.

Activity	Energy expenditure (Cal/m^2)
8 hr sleeping (35 Cal/m^2-hr)	280
8 hr moderate physical labor (150 Cal/m^2-hr)	1200
4 hr reading, writing, TV watching (60 Cal/m^2-hr)	240
1 hr heavy exercise (300 Cal/m^2-hr)	300
3 hr dressing, eating (100 Cal/m^2-hr)	300
Total expenditure	2320

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3-5 Regulation of Body Temperature

- People and other warm-blooded animals must maintain their body temperatures at a nearly constant level.
- A deviation of one or two degrees in either direction of normal temperature 37 °C may signal some abnormality.
- If the temperature-regulating mechanisms fail and the body temperature rises to 44°C or 45°C, the protein structures are irreversibly damaged .
- A fall in body temperature below about 28°C results in heart stoppage.
- The body temperature is sensed by specialized nerve centers in the brain and by receptors on the surface of the body.

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- The efficiency of muscles in performing external work is at best 20%
- At least 80% of the energy consumed in the performance of a physical activity is converted into heat inside the body .
- The energy consumed to maintain the basic metabolic processes is ultimately all converted to heat .
- If this heat were not eliminated, the body temperature would quickly rise to a dangerous level .

For example, during moderate physical activity, a 70-kg man may consume 260 Cal/hr. Of this amount, at least 208 Cal is converted to heat.

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- Most of the heat generated by the body is produced deep in the body, far from the surfaces.
- In order to be eliminated, this heat must first be conducted to the skin.
- For heat to flow from one region to another, there must be a temperature difference between the two regions.
- Therefore, the temperature of the skin must be lower than the internal body temperature.
- The tissue of the body, without blood flowing through it, is a poor conductor, its thermal conductivity is comparable to that of cork. (Kc for tissue without blood is 18 Cal/m-hr-C◦.)

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Assume that the thickness of the tissue between the interior and the exterior of the body is 3 cm and that the average area through which conduction can occur is $1.5 m^2$

The temperature difference between the inner body and the skin $2^{o}C$, the heat flow Q per hour is, $Q/t = \frac{(K_C A\ \Delta T)}{L} = \frac{18 \times 1.5 \times 2}{3} = 18\ Cal/hr$

In order to increase the conductive heat flow to a moderate level of say 150 Cal/hr, the temperature difference between the interior body and the skin would have to increase to about 17 ^{o}C.

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- Most of the heat is transported from the inside of the body by blood in the circulatory system.
- Heat enters the blood from an interior cell by conduction.
- In this case, heat transfer by conduction is relatively fast because the distances between the capillaries and the heat-producing cells are small.
- The circulatory system carries the heated blood near to the surface skin. The heat is then transferred to the outside surface by conduction.
- The circulatory system controls the insulation thickness of the body.
- When the heat flow out of the body is excessive, the capillaries near the surface become constricted and the blood flow to the surface is greatly reduced.

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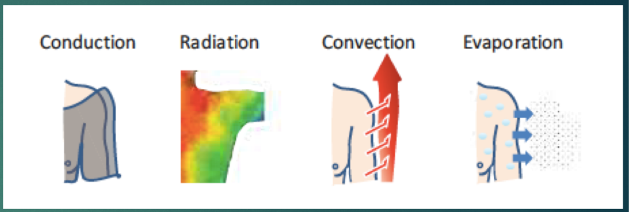
3-6 Heat losses of the body

The body features four mechanisms for heat loss to the environment.

1. Conduction
2. Radiation
3. Convection or wind chill
4. Evaporation or sweating and shivering



- The heat conductivity of air is very low. if the air around the skin is confined—for example, by clothing—the amount of heat removed by conduction is small.
- However, if the skin is in contact with a good thermal conductor such as a metal, a considerable amount of heat can be removed by conduction.

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1. **Conduction**: **The rate heat flow per unit time (Q/t)**

$$\frac{Q}{t} = \frac{(K_c\, A\, \Delta T)}{L}$$

ΔT difference between the inner body and the skin, K_c thermal conductivity L Thickness , A Area

2. **Convection or wind chill**: **The rate of heat flow (Q'_c)**

$$Q'_c = K'_c A_c (T_s - T_a)$$

A_c is the skin area exposed to the open air; T_s and T_a are the skin and air temperatures, respectively; and K'_c is the convection coefficient.

3. **Radiation: The rate of heat transfer per unit time(Q_r/t)**

$$\frac{Q_r}{t} = \sigma\, e\, A_r (T_s^4 - T_r^4)$$

T_s and T_r are the **skin surface** temperature and the temperature of the nearby **radiating surface** in (K), respectively; A_r is the area of the body participating in the radiation; $\sigma = 5.67\times10^{-8}$ J/(s. m^2. K^4) is the Stefan-Boltzmann constant. e is the emissivity (**For the skin, is usually taken as 1)**

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3-7 Work and power

- From the definition of energy (the capacity of doing work), we can conclude that wherever energy exists, there is a capability of doing work.
- Cells of the body store energy, so they are capable to do a work.
- When there is a consumption of energy there should be a work done.

The internal energy liberated (ΔE) during break down of a (fuel) molecule can perform a work (ΔW) and liberate a heat (ΔH) which can be given according to the first law of thermodynamics as follows: $\Delta E = \Delta W + \Delta H$

During the body metabolism there is, about 38% of the energy released from the fuel molecules is used as a work and the rest appears immediately as a heat.

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- The heat released in the body cannot be changed to work because our body is not a heat engine.
- But the heat is used to maintain the temperature of the body and the rest is dissipated outside of the body.

The power (*P*) is defined as the time rate (*Δt*) for doing work, Therefore $P = \frac{W}{\Delta t}$

Note that you do the same amount of work when you climb the stairs of a building in 2 min or 6 min, but your power output is not the same because it depends on the time interval of doing works.

The power of the cell for breaking glucose molecule at one second can be calculated from equation where energy of ATP which converted to work= 262 Kcal, therefore:

$$P = \frac{262Kcal}{1sec} = 262 \times 4184 = 1.1 \times 10^6 \frac{J}{sec} = 1.1\,MW$$

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3.8 Efficiency of the human Body

- We can consider the human body as a machine in doing external work.
- The efficiency is defined as the rate of the useful work output to the total input work:

$$eff = \frac{W_o}{W_i} = \frac{output\ work}{input\ work}$$

- The efficiency of all machine is less than 100%.
- Each cell is a machine which consume energy and it has a power and efficiency.
- The total energy supplied by glucose molecule is 686 Kcal which corresponds to the work input from which only 262 Kcal are used as an output work. Therefore,

$$eff = \frac{W_o}{W_i} = \frac{262}{686} = 38\%$$ Human cell efficiency

The efficiency of human made machine does not exceed 30% until now, which means that the cell of the body is more efficient than any human made machine.

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Example) Suppose your mass 60 kg, you climbed a hill of 20 m height during 5min and consumed 3 Lit of oxygen, calculate:

1- External work done by your body.

2- Power of your body.

3- Energy consumed in climbing the hill.

4- Efficiency of your body to climb the hill.

Solution)

1) $W = F.\Delta d = m.g.\ \Delta d = 60 \times 9.8 \times 20 = 11760$ J

2) $P = \frac{W}{\Delta t} = \frac{11760}{300\ sec} = 39.2W$

3) Since 1 Lit of O_2 consumed liberates energy around 5 Kcal. Therefore:

Energy consumed $= 3 \times 5\ Kcal = 15\ Kcal = 15\ Kcal \times 4184 = 62760\ J$

4) $eff = \frac{W_o}{W_i} = \frac{11760}{62760} = 18.73\%$

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