Institute for Christian Teaching
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BIOLOGICAL ENERGY TRANSFORMATION:

IMPLICATIONS FOR THE CHRISTIAN LIFE

by

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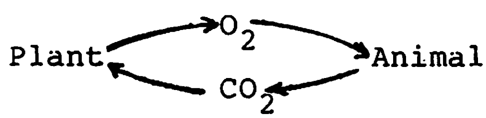
INTRODUCTION

The maintenance of life on earth requires the continual use of energy that comes directly or indirectly from the sun.[1] Plants directly get energy from the sunlight to combine carbon dioxide (CO_2) from the air and water from the soil to make food[2] through the process called photosynthesis. Whereas, animals derive energy (indirectly) from the food (carbohydrates, fats, and proteins) produced by the plants through the process of photosynthesis. This food is continually released in living cells during the process of respiration to produce energy. The energy released is either lost as heat or converted into energy-rich bonds in adenosine triphosphate (ATP). The energy temporarily stored in ATP is then used to carry out many energy-requiring reactions in the living cells.[3]

In essence, the entire living world depends on a series of reversible reactions between photosynthesis and respiration. In photosynthesis, CO_2 is taken in and oxygen (O_2) is released; in respiration, O_2 is taken in and CO_2 is released. This interrelationship can be seen in this diagram:



Thus Houston[4] has said "all creation, according to the Biblical story, is one system of interdependence. Grass depends upon the soil, animals upon the grass-- all life consists of interaction and interdependence."

It is the purpose of this paper to review the major steps in metabolic processes-- photosynthesis and respiration --and consider their implications for the Christian life, and to show man's dependence on the life-sustaining power of God.

FUNCTIONS OF PLANTS

The chief function and purpose of the plants in God's overall creation plan was to provide food for man and animals who were to inhabit this earth.[5] God said "Behold I have given you every herb bearing seed.... to you it shall be meat" (Gen. 1:29).

According to Rehwinkle,[6] God did three things to accomplish this purpose:

1. He created an almost infinite variety of plants to match the needs of the numerous variety of living creatures that were to fill the earth.

2. He created an abundant variety of plants so that there would always be sufficient supply at all times for

all creatures.

3. He provided the plant with a mysterious power to reproduce itself so that it would continue to provide food for all creatures and to meet the needs of the growing population of both man and animals.

Through these concerns, God had written His love in nature, That "God is love", Ellen White wrote. "is written upon every opening bud, upon every spire of springing grass."[7] Through nature we learn confidence and trust in God's love for "if God so clothe the grass of the field, which to day is, and to morrow is cast into the oven, shall He not much more clothe" us...?(Matt. 6:30). We need only to look at nature through the eye of faith.

PHOTOSYNTHESIS

The mysterious process of photosynthesis is considered as the most efficient manufacturing system known to man, and the wonder is that its operation is absolutely silent- no wear and tear in its mechanism.[8] During this process, plants capture carbon dioxide and using energy from visible light, build carbohydrates. But more significant than this is the by-product (oxygen) that sustains life since the beginning of time.

Although a knowledge of the minute details of the steps involved in conversion of light energy to chemical energy during photosynthesis is not necessary for an appreciation of the significance of the process, a consideration of the major steps in the reaction will help us understand the complexity of the reaction. Eventually, when more is known about the process, perhaps "man can take this knowledge and use light energy to produce food directly from the raw materials, carbon dioxide and water."[9]

"The fundamental significance of photosynthesis lies on its photosynthetic apparatus which is equipped with an intricate array of membranes and pigments."[10] This apparatus traps light energy and effects its conversion to chemical energy. We shall begin our study of photosynthesis with the pigments involved and their associated photosynthetic membrane structures--the chloroplasts.

CHLOROPHYLL

Chlorophyll, the pigment that makes leaves green, absorbs light in the violet and blue wavelengths and also in the red.[11] Of the total radiant energy that falls upon green leaves, about 80% is absorbed. Of the remaining 20%, a part is reflected from the leaf surface and a part passes through the leaf (transmitted). Part of the radiant energy absorbed is changed to heat and raises the temperature of the leaf; a large part of that absorbed is used up in transpiration; the remainder is utilized in photosynthesis and stored in carbohydrate molecules. Thus only about 0.5 - 3.5% of all the light energy that falls on the leaf is used in the process of photosynthesis.[12] This is a very low percentage when compared with the machine efficiency; however, the supply of solar energy is always continuous and abundant. Mommaerts[13] had estimated that the sun enriches the earth annually with about 5 X 10^{20} Kcal of radiant energy. Of this, only about 0.1% or 5 x 10^{17} Kcal per year is absorbed by vegetation and about 99.9% is absorbed directly by the atmosphere and the terrestrial surface; but this 0.1% Kcal per year enables the vegetation to assimilate about 80 X 10^{12} kg of CO2 and uses it to produce 55 X 10^{12} kg of organic matter annually.

Mommaerts further said that "the energy turnover in the bodies of the human population is of the order of 2 X 10^{15} Kcal, or nearly 0.5% of that of all living beings. Thus of the total energy flux received from the sun, 99% goes to heat directly, 0.1% through the total biosphere and 0.0004% through human population." This small part eventually goes to heat according to the second law of thermodynamics, which "states that heat is the end form of all energy transformations"[14], but along its pathways we live our lives and use the dissipated heat to maintain a constant body temperature.[15]

IMPLICATION

Just as there is continuous and abundant supply of solar energy, so is there abundant and free supply of God's grace. He promised "My grace is sufficient for thee" (2Cor. 12:9), and "He giveth grace unto the lowly" (Prov.3:34). He is "no respecter of person" (Acts 10:35). He pours His blessings to all. "He maketh his sun to rise on the evil and on the good and sendeth rain on the just and on the unjust" (Matt. 5:45). He is "kind unto the unthankful and to the evil" (Like 6:35).

"In the manifestation of God to His people, light had been a symbol of His presence. At the creative world in the beginning light has shone out of darkenss. Light had been enshrouded in the pillar of cloud by day and the pillar of fire by night, leading the vast armies of Israel."[16] "Just as the sunbeam penetrates to the remotest corners of the earth, so does the light of the Sun of righteousness shines upon every soul."[17]

But just as only the absorbed light is utilized in the process of photosynthesis, so only the truth that is believed and accepted into a human life by God's grace, can become alive, because the grace of God converts it into a warm, redeemed human heart. It is only when the truth is absorbed that transformation from sin to holiness by the interworking of grace and truth takes place repeatedly and continuously in faithful believers of every age and every land.[18]

However, to make God's grace our own, we must do our part. "His grace is given to work in us to will and to do, but never as a substitute for our effort"[19]

CHLOROPLAST

Chloroplasts are cytoplasmic organelles of greatest biological importance because they produce oxygen and most of the chemical energy used on planet earth by living organisms. Their number is relatively constant in the different plants. For example, the algae chlamydomonas often possesses a single huge chloroplast, but higher plants possess 20 to 40 chloroplasts per cell. It has been calculated that in a certain leaf, about 400,000 chloroplasts are present per square millimeter of surface area. These tiny organelles with the "average diameter in higher plants of 4 to 6 micrometer"[20] perform a tremendous work of food conversion ever known to man.

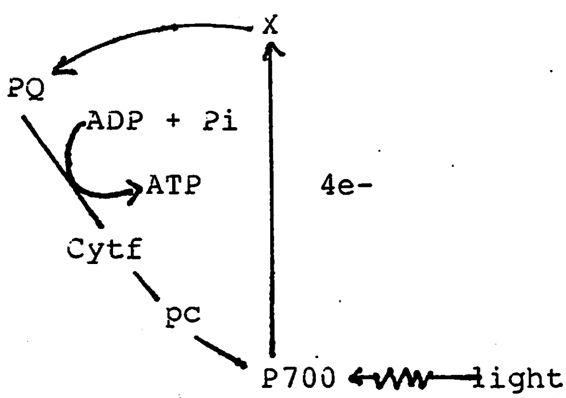
Chloroplasts contain pigment molecules that are arranged in precise and orderly fashion within the membranes of flattened sacs called thylakoids. The cholorophyll and accessory pigments in the thylakoids are organized into functional groups called photosynthetic units. Each unit contains some 300 pigment molecules including two slightly different kinds of chlorophyll (chlorophyll a and chlorophyll b) and carotenoids.[21]

Over 99% of the chlorophyll a molecules in the thylakoids and all of the functional chlorophyll b, carotenoids and other accessory pigments act as light harvesting pigments. They absorb light energy and transfer the resulting excited energy to other pigment molecules and eventually to a special form of chlorophyll a located in a reaction center.[22]

There are two kinds of reaction centers located in thylakoid membranes, and there may be several hundreds of each kind in each thylakoid. These reaction centers are called P680 and P700 because they absorb light with wavelengths of about 682 and 703 nm, respectively. Each reaction center is associated with a group of functional light-harvesting pigments. Hence, there are two kinds of pigment systems in thylakoid membranes-- photosystem I and photosystem II.[23] Let us review first the reactions involved in photosystem I and consider their implications.

PHOTOSYSTEM I (Cyclic photophosphorylation).

When a photon strikes one of the antenna pigments in photosystem I, it raises an electron in the pigment to a higher energy level. The excited electron then passed from one pigment molecule to another pigment molecule in a random sequence until it eventually reaches the reaction-center molecule (P700), a speciaized form of chlorophyll a, which traps it. This trapped electron is then passed (one at a time) from P700 to X, a very strong acceptor molecule, which passes it to a series of further acceptor molecules, each of a slightly lower energy level. As each acceptor molecule receives an electron, it becomes reduced (re) and as it releases the electron it becomes oxidized (ox). Eventually the electron returns to the chlorophyll from which it started.[24] "The electron tends to move rapidly, usually within a billionth (10-9) of a second,"[25] back into its original definite position around the nucleus (orbital). As it does this, the trapped energy is released. It may be given off as heat, or as light (fluorescence), or may be used to synthesize ATP from ADP and inorganic phosphate (Pi). The process below illustrates how ATP is formed.



Because the electron returns back to P700 and ATP is produced in the presence of light,[26] the process is also called cyclic photophosphorylation.

IMPLICATION

Just as the trapped light energy is given off as heat, or as light or converted to a usable form of energy (ATP), so is God's "energy" when received by a believer. It may be given off as light to a darkened soul or warmth to a cold heart or, as imparted courage that will energize the being back to a vibrant life in Christ. By reaching out and touching someone, we in return are blessed. Ellen White wrote:[27] "Every ray of light shed upon others will be reflected upon our own hearts. Every kind and sympathizing word spoken to the sorrowful, every act to relieve the oppressed, and every gift to supply the necessities of our fellow beings, given or done with an eye to God's glory, will result in blessings to the giver".

"The pleasure of doing good to others imparts a glow to the feeling which flashes through the nerves, quickens the circulation of the blood, and induces mental and physical health"[28].

Ellen white adds, "Those who, so far as it is posible, engage in the work of doing good to others by giving practical demonstration of their interest in them are not only relieving the ills of human life in helping them bear their burdens, but are at the same time contributing largely to their own health of soul and body".[29]

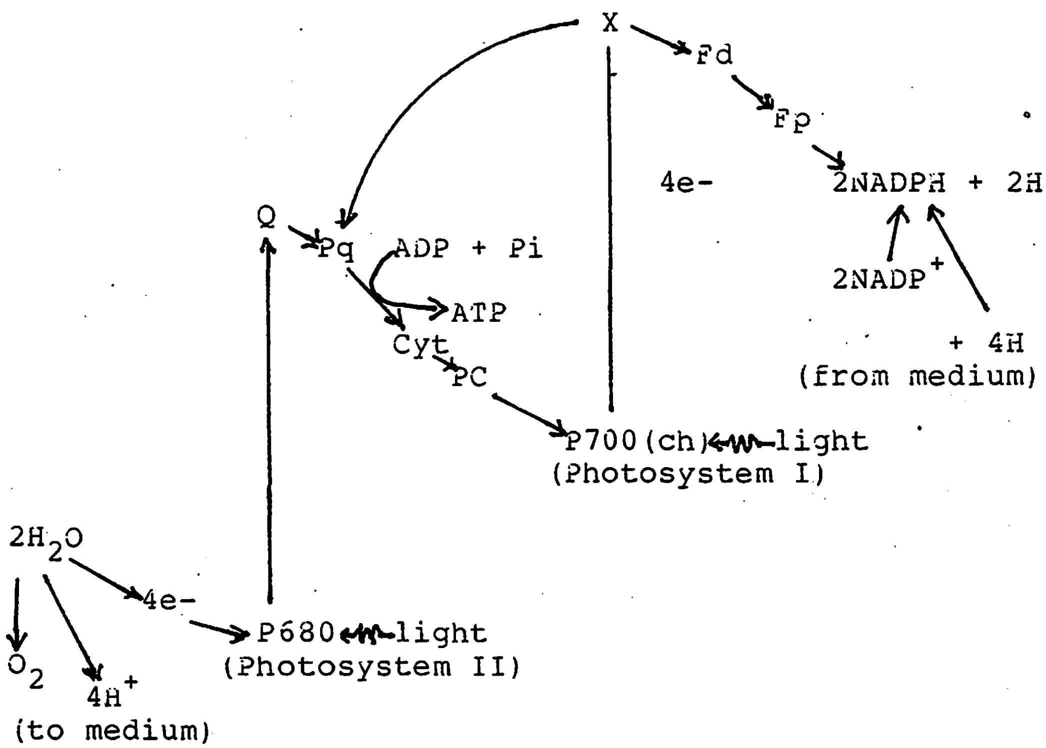
NADPH PRODUCTION (<u>Noncyclic Photophosphorylation</u>)

Like the process of cyclic photophosphorylation described above, this process according to Keeton[30] begins when photons of light strike molecules of chlorophyll in photosystem I and raise electrons to an excited state. Again, the excited electrons are led away from the P700 by strong electron acceptor, probably the one we have called X. But here the similarity to cyclic photophosphorylation ends. Instead of passing the electrons to the transport chain of cyclic photophosphorylation, X donates the electrons to a different series of electron-transport molecules, which in turn pass the electrons to an extremely important substance called nicotinamide adenosine dinucleotide phosphate ($NADP^+$ -- in an oxidized form). The $NADP^+$ can accept two electrons and a hydrogen ion, and is thus reduced to NADPH. In this process, as outlined below with photosystem II, another H^+ ion is released into the environment. The NADPH can eventually act as an electron donor in the reduction of CO_2 to carbohydrate.

Now, if the energized electrons from the chlorophyll of photosystem I are retained in NADPH and eventually incorporated into carbohydrate, it follows that photosystem I is left short of electrons, that it is left with "electron holes". These electron holes are filled, indirectly, by electrons derived from water as a result of a second light event. This second light event involves photosynthetic units of photosystem II.

PHOTOSYSTEM II

When light of the proper wavelength strikes a pigment molecule of photosystem II, the energy, in the form of excited electrons, is passed around within the photosynthetic unit until it finally reaches the molecules of P680. According to Keeton and Mcfadden[31] this molecule, in turn, donates the high-energy electrons to a strong electron acceptor, designated as Q. Substance Q then passes the electron to a chain of acceptor molecules, which lead the electron holes in photosystem I. As the electrons move along the chain of transport molecules, they are eased step by step down an energy gradient. Some of the energy thus released is used in the synthesis of ATP and inorganic phosphate. The flow of electron from water to photosystem II to photosystem I is illustrated below:



Thus the electron holes created in Photosystem I by the first light event are refilled by electrons moved from photosystem II by the second light event. But this process alone would leave photosytem II one electron less. The electron deficit would simply have been shifted from photosystem I to photosystem II. It is at this point that the electrons from water play their role. It is thought that P680 pulls replacement electrons away from water, leaving behind free hydrogen ions and molecular oxygen.

The hydrogen ions, as shown above, become associated with $NADP^+$ to form NADPH plus H^+. The oxygen released as a gaseous by-product (note that two molecules of H_2O must be split to yield one molecule of O_2 is used by living cells in the process of respiration, without which there is no life on earth.

Thus in the light, there is a continuous flow of electrons from water to photosystem II to photosystem I to $NADP^+$. The energy harnessed from these steps is represented by an ATP and NADPH, which then becomes the chief source of energy for the reduction of carbon.

IMPLICATION

The continuous flow of electrons from water to photosystem II to photosystem I to NADPH illustrates the continuous flow of God's love to the world through His children. Griffith Thomas said, "God's love is only made available for others through His children, for this reason believers are to be 'means of grace'. The truth needed for salvation, the comfort needed for cheer, the holiness needed for living are mediated by us to others, and in proportion as they see the love of God in us will our lives be means of grace to them. Grace will make us gracious in our dealings and enable us to avoid the spirit of hardness, hatred, severity, and manifest the spirit of love, patience, mildness, forgiveness, and tenderness. The love of God in our hearts will lead to the love of God in others, and all our relationships will be sweetened, hallowed, purified, uplifted, and transfigured."[32]

"In the matchless gift of His Son, God has enriched the whole world with an atmosphere of grace as real as the air which circulates around the globe. All who chose to breathe this life-giving atmosphere will live and grow up to the stature of men and women in Christ Jesus."[33]

THE CALVIN CYCLE

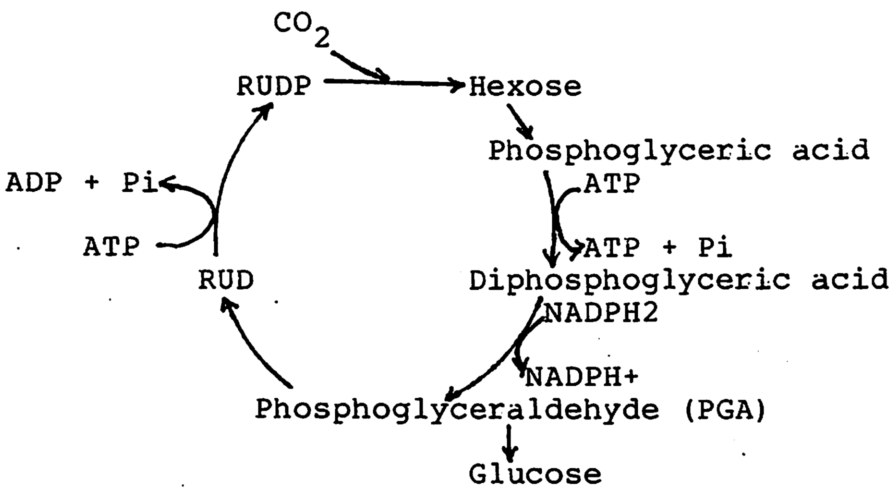
The reduction of carbon dioxide to organic carbon occurs in the stroma of the chloroplast. This is accomplished by means of the Calvin cycle. The starting (and ending) compound in this cycle is a five-carbon sugar with two phosphates attached to ribulose diphosphate (RUDP). According to Curtis,[34] the cycle begins when carbon dioxide enters the cycle and is bound to RUDP, which then splits to form two molecules of phosphoglycerate or PGA.

As illustrated below, at each full turn of the cycle, a molecule of carbon dioxide that enters the cycle, is reduced, and a molecule of RUDP is regenerated. Six revolutions of the cycle, with the introduction of six atoms of carbon, are necessary to produce a six-carbon sugar, such as glucose.

The three-carbon sugar (PGL) produced by Calvin cycle and those derived from it provides:
(1) the energy source for all living system, and (2) the

basic carbon skeleton for all organic molecules.

Molecules of glyceraldehyde phosphate may flow into a variety of different metabolic pathways, depending on the activities and requirements of the cell. Often they are built up to glucose or fructose, (following a sequence that is in many of its steps the reverse of the glycolysis sequence). Plant cells use these six-carbon sugars to make starch and cellulose for their own purposes and sucrose for export. Animal cells store them as glycogen. All cells use sugars, including glyceraldehyde phosphate and glucose, as the starting point for the manufacture of their carbohydrates, fats and other lipids, and with the addition of nitrogen, amino acids and nitrogenous bases.



IMPLICATION

The presence of light leads to the production of two energy-rich compounds-- ATP and NADPH, but it does not directly synthesize carbohydrate. It is up to the cell to utilize these energy-rich compounds in the production of carbohydrate. Likewise, "the agency of the Spirit of God does not remove from us the necessity of exercising our faculties and talents, but teaches us how to use every power to the glory of God. The human faculties, when under the special direction of the grace of God,[35] are capable of being used to the best purpose on earth."

A green plant is a machine that runs on solar energy. Light powers photosynthesis. In effect the plant captures the energy of the sun and converts it into the substances that directly or indirectly sustain most other forms of life on the earth.[36] Without this process, animals and humans would starve to death. Thus Houston added: "the energy of God's will, not just the energy of the sun, sustains the biosphere where grass grows and animals feed and man depends upon them for his own food".[37]

It is a mistake, however, to think that to a plant, light is no more than a fuel. "Even before a nascent shoot splits its seed coat, light or the lack of it rules a plant's life. Light can tell a plant how high to grow, how many leaves to sprout, when to flower and to set fruit, and when at last to age. More than just a power supply for photosynthesis, light dictates a plant's very form through a process called photomorphogenesis."[38] Likewise if we allow the "light of the world" to control our lives, and in all our ways acknowledge Him, then He will direct our paths (Prov. 3:6).

RESPIRATION

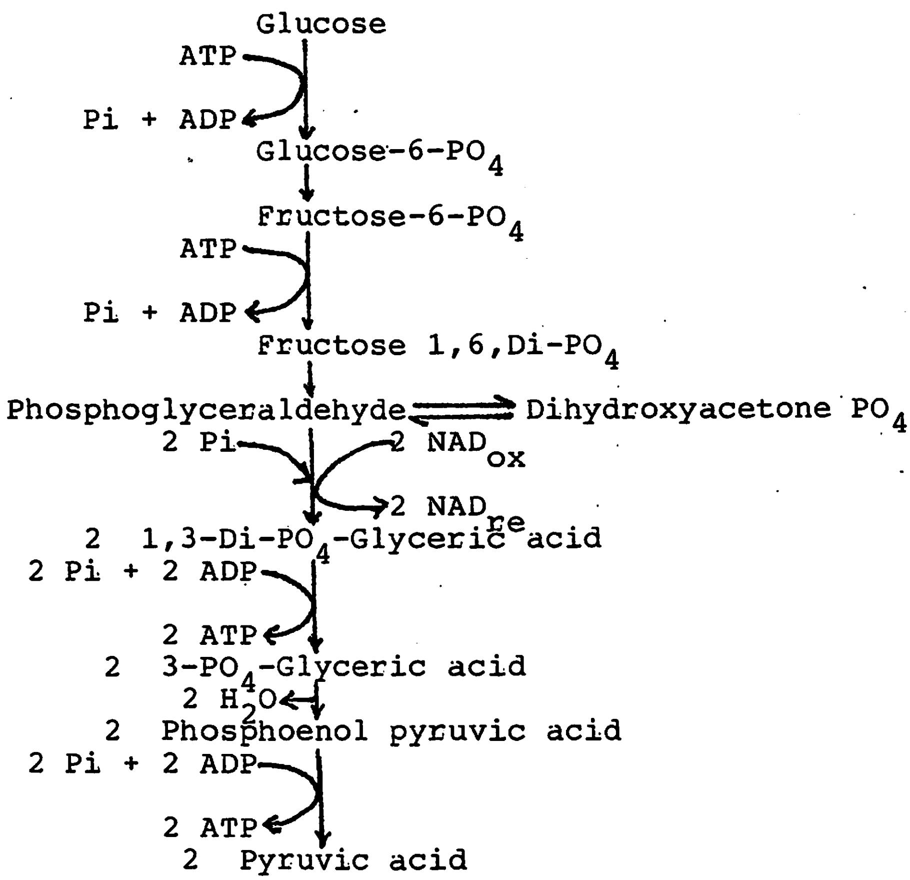
All living cells require energy to maintain their structural integrity and to perform numerous functions. In plants, differential permeability cannot be maintained without a supply of energy. Roots will not accumulate solutes and protoplasm will not move without energy from respiration. The synthesis of new cellular materials such as amino acids, proteins, fats and growth itself-- all require energy from respiration.[39] In human beings the beating of the heart, the digestion and the absorption of food, the building and repair of tissue, etc., cannot occur without energy. In fact, the very organization of each living cell depends on complicated chemical reactions that require a constant supply of energy. Without energy there is disorganization of cells, and eventually, death.[40] To acquire this required energy, the cells must break down complex organic molecules (food) through the process called respiration.

We shall begin our examination of respiration with the anaerobic breakdown of glucose to pyruvic acid-- a process known as glycolysis.

GLYCOLYSIS

Glucose is a stable compound, which has a little tendency to break down to simpler products. To release the energy locked in its chemical bonds, the cell must invest a small amount of energy (activation energy) to initiate the glycolytic process.

In the process, glucose is coverted to glucose-6-phosphate which in turn is converted to fructose-6-phosphate which is further converted to fructose 1, 6-diphosphate. For each mole of glucose that enters the pathway, two moles of ATP donate terminal phosphate groups to convert glucose into fructose 1, 6-diphosphate. Once fructose 1, 6-diphosphate has been formed, the pathway diverges by splitting the fructose diphosphate into two three-carbon molecules. One of the three-carbon molecules is glyceraldehyde-3-phosphate (PGL). The other, dihydroxyacetone phosphate, is converted into glyceraldehyude-3-dphosphate by a separate chemical reaction. Thus, from fructose 1, 6-diphosphate two molecules of glyceraldehyde-3-phosphate had been produced. But instead of releasing energy from the carbohydrate and forming new ATP molecules, glycolysis had actually resulted in the loss of two molecules of ATP. All the reactions up to this point have been preparatory. Through a series of reactions outlined below, glyceraldehyde -3-phosphate is converted into pyruyic acid which may be further oxidized in the Krebs cycle.[41]



The next reaction, a rather complicated one that begins the changes leading to production of new ATP, is really two reactions in one, according to Keeton.[42] The PGL is both oxidized and phosphorylated. The free ends of the two PGL molecules are phosphorylated with inorganic phosphate: the result is two molecules of three-carbon compound with a phosphate group at each end. In the process, the PGL molecules are oxidized: four electrons and two hydrogen ions are removed and picked up by molecules of the electron acceptor NAD^+ (an oxidized form of Nicotinamide Adenine Dinucleotide) and, two addition hydrogen ions are released. Each molecule of NAD^+ can accept two electron and one hydrogen ion.

An important feature of glycolysis is that it can generate a limited number of ATP in the absence of oxygen. Some cells, such as muscle cells, may rely heavily upon the anaerobic formation of ATP. But other cells are so sensitive to the absence of oxygen that they cannot survive for more than a few minutes in its absence. The reason becomes clear when we consider the oxidation of glucose in the absence of oxygen (in glycolysis). From the oxidation of glyceraldehyde-3-phosphate, one of the products of the reaction is NADH. The formation of NADH occurs at the expense of one of the reactants, NAD^+. Since NAD^+ is necessary reactant in this important step of gycolysis, it must be rejuvenated from NADH. If it is not reformed, the process will stop. Moreover, in the absence of oxygen, NADH cannot be reoxidized back to NAD^+ in the electron-transport chain: oxygen, the final acceptor of electrons must be present.[43]

However, in the fermentation process NADH can be used as an electron donor in the reduction of pyruvic acid to lactic acid. The conversion of pyruvic acid to lactic acid is particularly important in muscle cells when they are undergoing strenuous activity. Under these conditions the oxygen supply cannot keep pace with oxidative metabolism and the cells continue metabolism by producing lactic acid which diffuses out into the bloodstream. When oxygen once again becomes available in sufficient amounts, the lactic acid can be converted back to pyruvic acid for continued oxidation.[44]

Under strenuous exercise, the muscle cells used up oxygen faster than the body can supply. If for any reason a person is unable to repay his oxygen debt and cannot prevent the accumulation of lactic acid, muscle fatigue will result. Excessive amounts of lactic acid tend to depress the activity in muscle cells, leading to decreased irritability and interfering with their ability to contract. Therefore, if the recovery phase lags too far behind the contraction phase, the muscles will be physically unable to respond in their usual efficient manner, thus "forcing" one to stop his activity and rest until conditions return to normal.[45]

In most cells, molecular oxygen if available, becomes the ultimate acceptor of electrons from NADH, by a process we shall examine later. But under anaerobic conditions, with no O_2 to accept the electrons, the pyruvic acid formed by glycolysis accepts electrons from

NADH . This reduction of pyruvic acid results in the formation of lactic acid in animal cells or in the formation of ethyl alcohol, plus CO_2 in plant cells and in many unicellular organisms.[46]

IMPLICATION

The need to convert pyruvic acid to lactic acid when insufficient NAD^+ is present illustrates how sensitive metabolism is to the concentration level of various metabolites. These concentrations must be very carefully controlled by a complex variety of regulatory mechanisms God has installed in human system. As metabolism is sensitive to the concentration of metabolites, so is the Holy spirit sensitive to man's response to His pleadings. Thus we are warned about resisting, grieving, and quenching the Spirit (Acts 7:51;Eph.4:30;1Thess.5:19).

"Today the Holy Spirit directs our attention to the greatest gift of love God proffers in His Son. He pleads that we not resist His appeals, but accept the only way whereby we can be reconciled to our loving and gracious Father."[47]

The all-loving God created the plants not only to supply food but also to release a life-sustaining gas-oxygen. No man can live longer than five or six minutes without using the oxygen released by the plants. Our lungs, blood, and body tissues carry approximately two quarts (1.2 liters) of oxygen. If cut off from oxygen, these two quarts would last the body for about four minutes. The body cells most affected by the lack of oxygen are in the brain, especially the higher centers that deal with reason, will power, judgment and emotion.[48] Since God communicates with us through our conscience, and we make decision after critical thinking, adequate supply of oxygen is vital to good judgment. God provides adequate and abundant supply of oxygen; but when man avails not himself with this supply, his body is affected. If oxygen intake is reduced through improper respiration (shallow breathing), drowsiness and susceptability to disease will result. "Shallow breathing not only has an adverse effect on the lungs; the stomach, liver and brain are also affected."[49]

ANAEROBIC RESPIRATION

In the presence of abundant molecular oxygen, the metabolic breakdown of glucose initially follows the glycolytic pathways to pyruvic acid. But in the presence of O_2, which can act as the ultimate acceptor of electrons from NADH, pyruvic acid need not act as an electron acceptor and become converted into lactic acid or alcohol. Instead, it can be further broken down and yield energy for synthesis of still more new ATP. In other words, under aerobic conditions, ATP synthesis does not end with the pyruvic acid step. Indeed, if lactic acid has already been formed, it may be reconverted into pyruvic acid, with accompanying resynthesis of NADH, when sufficient oxygen becomes available. This pyruvic acid, may then be further oxidized; much energy is still locked in this compound.[50]

OXIDATION OF PYRUVIC ACID TO ACETYL CoA

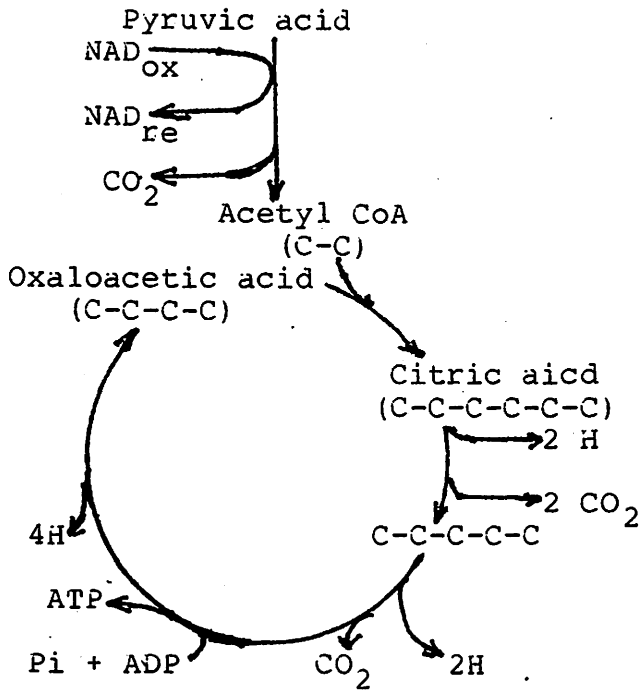
The aerobic oxidation of pyruvic acid begins with a complicated set of reactions whose net effect is to break down the tree-carbon pyruvic acid to CO_2 and an activated form of the two-carbon compound acetic acid. The acetic acid is said to be activated because it is not present as free acetic acid , but is bonded to a coenzyme called coenzyme A, or CoA for short; the complete compound is called acetyl-CoA. When a molecule of pyruvic acid is oxidized to acetyl-CoA and CO_2, hydrogen is removed and a molecule of NADH is formed. Since two molecules of pyruvic acid were formed from each glucose molecule, two molecules of NAD_{re} are formed here. This process is shown together with the Krebs cycle below.

KREBS CITRIC ACID CYCLE

As outlined below, the acetyl-CoA is next fed into a complex series of reactions called the Krebs citric acid cycle. This cycle starts with the two two-carbon acetyl-CoA combining with a four-carbon compound (oxaloacetic acid) already present in the cell, to form a new six-carbon compound called <u>citric acid</u>. According to Keeton and Mcfadden[51], each of the citric acid molecules is then oxidized to a five-carbon compound plus CO_2. The five-carbon unit, in turn, is oxidized to a four-carbon compound plus CO_2. This four-carbon compound is then converted into the same four-carbon compound as the one to which acetyl-CoA was originally attached; it can now pick up more acetyl-CoA, forming new citric acid and beginning the cycle again.

Since each glucose molecule being oxidized yields two molecules of acetyl-CoA, two turns of the cycle are required, and a total of four carbons are released as CO_2 during this stage of glucose breakdown. With the two other carbons already released as CO_2 during the oxidation of pyruvic acid to acetyl-CoA, all six carbons of the original glucose are accounted for.

The oxidative breakdown of each molecule of acetyl-CoA via the Krebs citric cycle also involves the removal of eight hydrogen, which are picked up by NAD_{ox} (or by a related electron-carrier compound called FAD_{ox}); four units of reduced carrier are thus formed. Since the breakdown of one molecule of glucose leads to two turns of the Krebs cycle, a total of eight molecules of reduced carrier (6 NAD_{re} and 2 FAD_{re}) are formed during this stage of the breakdown of glucose. Two molecules of ATP are also synthesized (as a result of substrate level phosphorylation) in the Krebs cycle. This reaction is diagramed below:



RESPIRATORY ELECTRON-TRANSPORT CHAIN

In our examination of the three stages of catabolism- glycolysis, conversion of pyruvic acid into acetyl-CoA, and the Krebs cycle- we have so far seen a net gain of only four new ATP molecules (two in glycolysis and two in the Krebs cycle). These represent but a small fraction of the energy originally available in the glucose. The rest of the energy is still locked up in pyruvic acid[52]

Under aerobic conditions, as described by Keeton, the regeneration of NAD_{ox} from NAD_{re} is achieved by passage of the hydrogen (especially hydrogen electrons) from NAD_{re} to O_2: In other words, O_2, acts as the ultimate acceptor of hydrogen, and water is formed:

$$O_2 + 2\ NADH + H+ \text{ -- } 2H_2O + 2\ NAD_{ox}$$

The NAD_{re} does not, however, pass its hydrogen directly to the oxygen, as this summary equation might seem to indicate. What happens, instead, is that the hydrogen electrons are passed down a "respiratory chain" of electron-transport compounds, many of which are iron-containing pigments called cytochrome. In this manner, the electrons are lowered step by step from their high energy level in NAD_{re} to a low energy level in H_2O.

As the electrons are lowered down the energy gradient step by step through the respiratory electron-transport chain, energy is released and some of this energy is used in the synthesis of ATP from ADP and inorganic phosphate. This process, often called "oxidative phosphorylation", is very similar to the electron transport and ATP synthesis of photophosphorylation already discussed.

TOTAL ATP YIELD

The yield of ATP molecules from the complete metabolic breakdown of one molecule of glucose to carbon dioxide and water is summarized as follows:

1. Altogether, 36 new ATP molecules are formed which are about 38 percent of the free energy initially present in the glucose.
2. Only two of the 36 ATP molecules (about 6 percent) are synthesized anaerobically ; the other 34 (about 94 percent) are the product of aerobic respiration.
3. Of 34 aerobically synthesized ATP molecules, 32 result from electron transport via the respiratory electron-transport chain and 2 from the Krebs cycle.

IMPLICATION

The most significant product of respiration is the production of energy in the form of ATP. That only 2 ATP of the 36 ATP are synthesized in the absence of oxygen indicates the essentiality of oxygen to the life of human beings and most other organisms. That of the 34 aerobically synthesized ATP molecules, 32 result from electron transport chain, points the critical importance of the chain, and makes it easy to understand why cyanide and certain other poisons that block the chain are lethal. In like manner, sin can block the spiritual process and destroy God's image in man. Ellen White said "one cherished sin is suficient to work the degradation of the characters."[53] She emphasized that "if the foot or the hand would be cut off or even the eye would be plucked out, to save the body from death, how much more earnest should we be to put away sin, that brings death to the soul!"[54] As poison blocks the electron transport chain, thus stopping the aerobic metabolism, so is sin of any form. "Every impure thought defiles the soul, impairs the moral senses, and tends to obliterate the impressions of the Holy Spirit."[55]

Jesus made reference to the wind to demonstrate the working of the Holy Spirit. The wind (air in motion) contains 21% of oxygen. It is in its presence that energy stored in the food is released, providing man the energy to think, to communicate, to act according to the needs and demands of the body. Likewise, the Holy Spirit releases the "spiritual energy" stored in the mind. Jesus said, when the Comforter shall come "He shall teach you all things, and bring all things to your remembrance." (John 14:26) "He will guide you in all truth"(John 16:13). Just as the product of respiration is energy, so is the result of the presence of the Holy Spirit in the life. Jesus said, "And ye shall receive power after that the Holy Ghost is come upon you" (Acts 1:8).

CONCLUSION

Plants transform light energy by the photosynthetic action of chlorophyll into chemical energy and store it in the bonds of organic compounds. In this process, carbon dioxide is taken in and oxygen is released. Chemical bonds in the organic molecules represent stored or potential energy. Some of this is used by the plants themselves in synthesizing other of their own necessary components. The energy needed by animals is obtained either directly by feeding on plants or secondarily by eating other plant-consuming animals. Animals use glucose, by respiration, to derive most of their energy, giving off CO_2 and H_2O as by products[56].

Before God created life, He first created the things that it needed. He created the light and the atmosphere before He created the plants and the animals. Since creation, the sun had provided light to the plants as their source of energy. Through this energy, plants are able to manufacture food for themselves and for other living organisms. "Without light there could be no life; and as the Creator began the work of bringing order from chaos and of introducing various forms of plant and animal life upon the earth, it was essential that there be light."[57] The essentiality of the physical light to the physical life illustrates the essentiality of the spiritual light to our moral and spiritual life. That the sun is the center of the solar system, illustrates the centrality of Christ in our spiritual solar system.[58] Without Christ in the life, we are nothing. "For in Him we live, and move and have our being" (Acts 17:28).

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