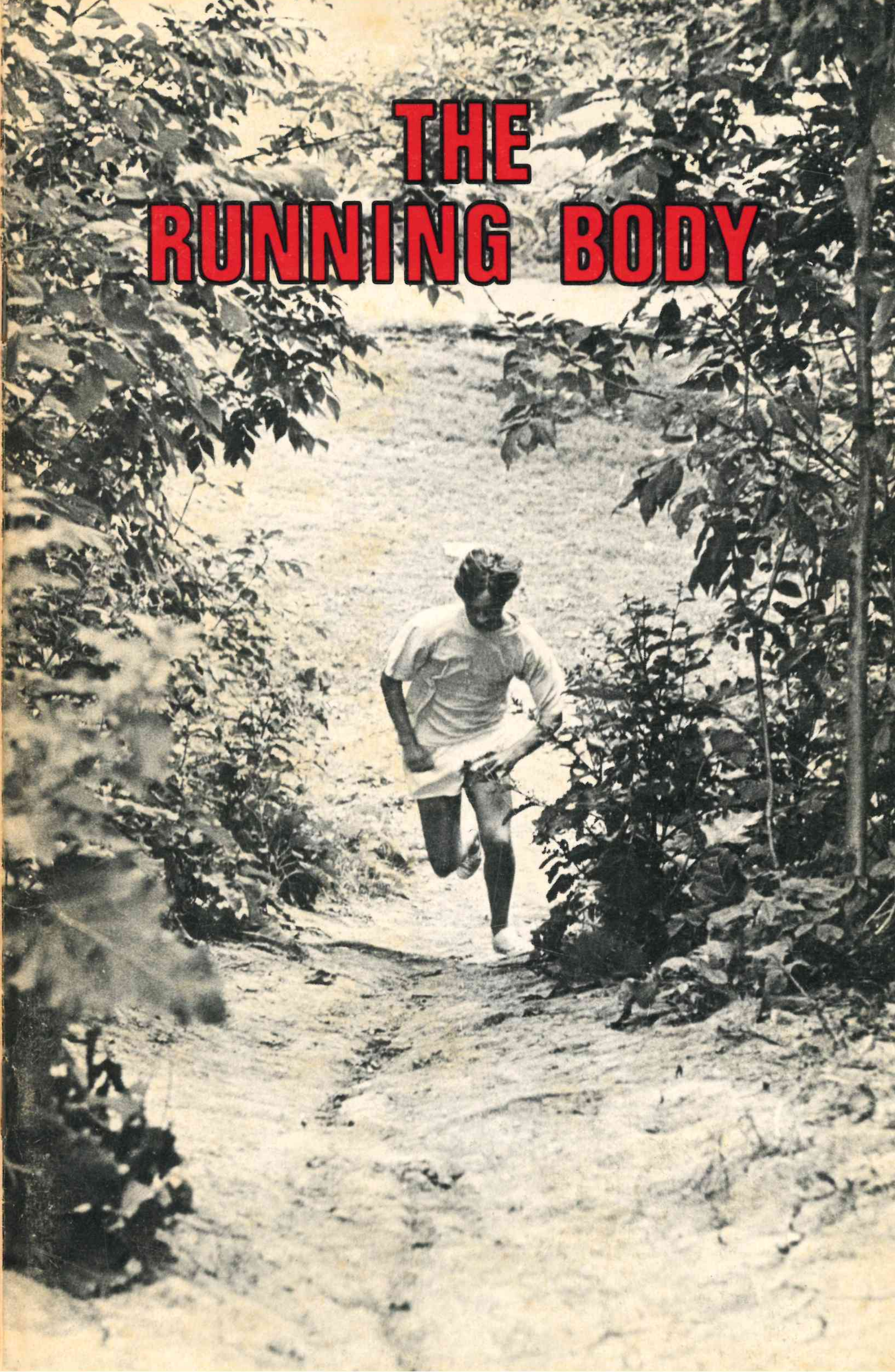
THE RUNNING BODY



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THE RUNNING BODY

by E.C. Frederick

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FOREWORD

The fact that Roger Bannister was a student of medicine is of more than incidental significance. For years, the four-minute mile loomed as an insurmountable barrier–defying the strongest, the fastest, the best prepared. Many experts of the day produced elaborate calculations showing that it was impossible for the human machine to run faster than four minutes for the mile. Time after time, the world's fastest milers came within a breath of this ultimate athletic goal. But all failed, unable to overcome the limits of their minds.

Roger Bannister was different. He had studied the functional capacities of the body and he *knew* that 3:59 was well within his capability. It was this knowledge and an understanding of the function of the running body that allowed Bannister to succeed where so many others had failed.

World records and other friends of the ego aside, there is great pleasure in running. The greatest reward of knowledge is not that it can aid us in achieving our goals, but that it can add dimension and enjoyment of what we do. Thus the experience of running can be so much richer if we understand the subtle physiologic changes we undergo in training and during a race.

What happens, physiologically, during a year of training to allow a former arm-chair athlete who couldn't wheeze through a mile in 10 minutes to string together 26 sub-seven-minute miles for a three-hour marathon? What causes cramping? How does carbohydrate-loading work? What is fatigue? How does altitude training enhance performance?

To understand the vast array of physiological adjustments we undergo in months of training, and to realize the *raison d'etre* or the multitude of aches and pains we feel is to experience running more fully. It is toward this end that this booklet is written.

With a knowledge of the basic physiological aspects of running, we can more easily achieve our personal goals while at the same time add a new dimension to the experience of running.

E. C. Frederick
Flagstaff, Ariz.
August, 1973

The Author: *At the time he wrote this booklet, E. C. "Ned" Frederick was studying for his doctorate in zoology at Northern Arizona University. His research involved a comparative study of three different types of running training–long interval, short interval and continuous running–on the muscle tissues of laboratory rats.*

Frederick has an extensive academic background in exercise physiology, as well as practical experience as a middle and long distance runner.

Chapter 1

THE BASICS

"When you consider that the amount of food that can be taken in during a run (via Gatorade, ERG, etc.) is small to non-existent, it is apparent that we must rely heavily on our energy stores to supply the fuel our bodies require..." (Sharran Herriot photo)

RUNNERS' ENERGY NEEDS

As we begin the transition from the moderate activity of walking to the intense effort of running, many changes take place. For example, we are immediately aware of an increase in heart rate, perspiration rate and respiration rate.

The miles of training that have gone before to allow us to enjoy this run have also produced noticeable changes. We notice that we can run faster and with less effort. It takes less time for our heart rate to return to normal following a run. We may experience a feeling of having more "energy," of greater facility in performing physical as well as mental tasks.

All of these changes—both acute (with each run) and chronic (longer lasting, basic physiologic changes)—represent the tips of so many icebergs. For underlying each of these easily observed gross changes are a number of alterations in the physiology of the cells involved.

To fully understand what is happening within the running body, we must go beyond the systemic level and explore the function of the cells. This knowledge is basic to a complete understanding of all aspects of the physiology of running.

To the runner, the word "energy" has a particular significance. Although we all require large amounts of energy to live out each day, the runner has put himself in a position of requiring considerably more than the average individual. But even beyond this quantitative difference, the runner must have specially adapted and developed physiological systems for utilization and storage of energy sources.

What substances supply us with the energy we need? And how are these substances utilized to provide us with the energy to perform the formidable task of running, for example, a marathon?

The energy requirements for running a three-hour marathon are considerable. An average figure is 2500 calories. (The calorie is actually a kilocalorie, When we talk about calories in food, etc., we are talking kilocalories or thousands of calories.)

Twenty-five hundred calories is more energy than the average sedentary individual requires to get through a 24-hour period. When you consider that the amount of food that can be taken in during a run (via Gatorade, ERG, etc.) is small to non-existent, it is apparent that we must rely heavily on our energy stores to supply the fuel our bodies require to sustain such an increased output.

The major energy storage components of the body are fats, and liver and muscle glycogen. As you'll see later, muscle glycogen is the most important, in terms of performance. But fats also play an important role.

Before we can fully understand the function of either of these storage products, we must comprehend the basic cellular events which underlie all energy metabolism.

HARNESSING ENERGY

Carbohydrates come in many forms. Starches, glycogens and sugars are the forms the most familiar. Starches and glycogens are polymers of sugars, i.e. complex molecules made up of many individual sugar molecules linked together in a specific fashion (see Figure 1). These polymers store sugar molecules like the links in a chain of sausages. As the sugars are required, they are chopped off the ends of the chain and pass into the metabolic machinery of the cell.

Glucose (also known as dextrose or blood sugar) is the major sugar molecule making up starches and glycogens. It is the prime fuel of our biological engines. We can acquire the glucose we need from storage compounds in our own bodies, or we can ingest it.

We take in glucose in a number of ways: in bread (the starch in bread consists of glucose molecules linked together in long branched and unbranched chains), in cane sugar (called sucrose, which is a glucose and a fructose molecule bonded together), in honey (which is a mixture of glucose and fructose molecules, the bees having provided the means for separating the two parts of sucrose), and in a tremendous variety of other foods. Almost all foods contain some carbohydrate.

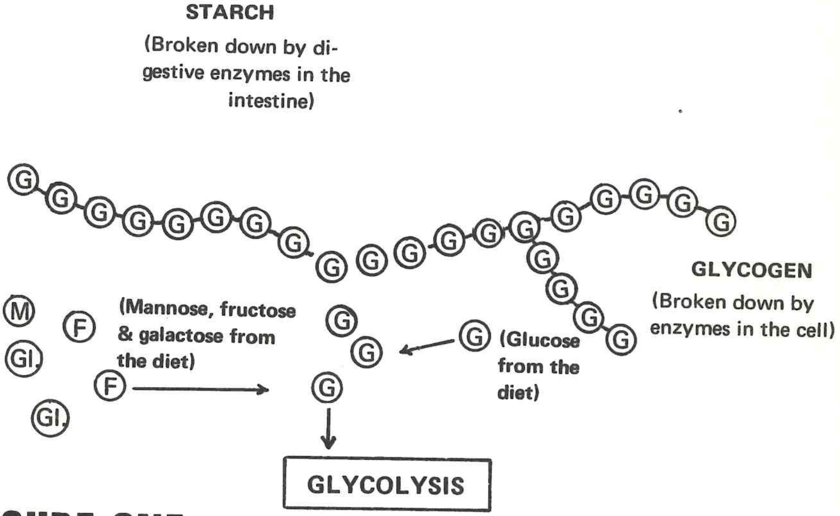


FIGURE ONE Carbohydrates Burned for Energy

Once we have the glucose in the cell, we must somehow extract some of its energy. The energy that our cells garner from the metabolism of glucose molecules is from the chemical bonds (which hold its six carbon, 12 hydrogen and six ogygen atoms together). Considerable energy is present in the bonds of glucose. If we were to take a tablespoon of glucose and somehow break all of its bonds (such as by burning it) approximately 45 calories of energy would be given off in the form of heat.

If this were the way our bodies used glucose, we would all instantly burst into flames. Fortunately, the wisdom of evolution has developed an ingenious process for harnessing the bond energy of the glucose molecules which considerably reduces the loss of energy as heat.

The cell accomplishes this conservation of energy by utilizing a series of enzymes which direct a succession of discrete changes in the structure of the glucose molecule. These changes gradually break the glucose molecule down—step by step, rather than all at once—until all that is left is carbon dioxide and water. Along the way, 38 adenosine triphosphate (ATP) molecules are netted. The energy from the chemical bonds of glucose is thus stored in the ATP molecules' chemical bonds for use in the body's energy requiring functions.

There are three basic components involved in the metabolism of glucose: glycolysis, the Krebs Cycle and the electron transport system (ETS). Each in its own way contributes to the energetics of the cell, and thus each has its particular significance to the runner.

GLYCOLYSIS MECHANISM

Glycolysis provides intermediate compounds which may enter into the Krebs Cycle, as well as producing a net two ATP molecules along the way. This may not seem like a lot compared to the 38 ATP total, until you realize that the formation of the other ATPs requires oxygen. The ATPs formed in glycolysis can be produced in an oxygen-free anaerobic state.

The terms aerobic and anaerobic exercise refer to the presence or absence of oxygen in the muscle cells and other cells of the body. If we are performing an exercise so strenuous that the need for oxygen in the cells exceeds the capability of our bodies to take up and transport oxygen to these tissues, then we are exercising in an anaerobic state. If the demand for oxygen doesn't exceed the supply, then the exercise is aerobic.

Seldom is an exercise either/or. In reality, there is usually a combination of the two states during running. We could say that marathon running is 95% aerobic, the 100-yard dash 95% anaerobic, and most other races somewhere in between. However, this often depends on the stage of the race as well as the distance, speed, etc.

The significance of glycolysis is that if a certain cell does not have sufficient oxygen, then energy can still be produced. Thus, in the dead sprint at the end of a three-mile, we are in mostly anaerobic state. This means that we are relying heavily on glucose to produce the energy we need to catch Mr. X at the finish.

This sounds like a nice solution to the problem, and it would be if it weren't for lactate (a form of lactic acid). Without oxygen to receive the electrons at the end of the electron transport system (ETS), there is a backup in the ETS and the Krebs Cycle (see Figure 5). This means that the normal products of glycolysis can't enter the Krebs Cycle. This backup plus the demand for certain molecules essential to glycolysis itself cause lactate to be the end product of glycolysis (see Figure 2). Since only two ATPs are netted per glucose molecule, more and more glucose must be passed through glycolysis to produce the same volume of ATP as when oxygen is present.

This means that tremendous amounts of lactate are produced. This production far exceeds the body's capacity to break it down. The result is a buildup of lactate, which gradually makes the environment of the cell more acidic until the enzymes and other important molecules are unable to function.

The gross results are familiar to many of us: weakness, cramping and general pain. After the anaerobic activity is finished, we continue breathing hard while the muscles and the liver oxidize the tremendous buildup of lactate. Once this is accomplished, we can return to a normal breathing rhythm.

Starting with either glycogen or glucose (other sugars such as fructose, mannose and galactose can be processed also), glycolysis will produce two pyruvate molecules, regardless of the presence or absence of oxygen. These pyruvates can then become lactates (if not enough oxygen is present; actually, there is always a certain amount of lactate produced regardless of oxygenation, but increasing amounts are produced as the oxygen supply diminishes). Or, more commonly, the pyruvates can become two acetyl Co-A molecules.

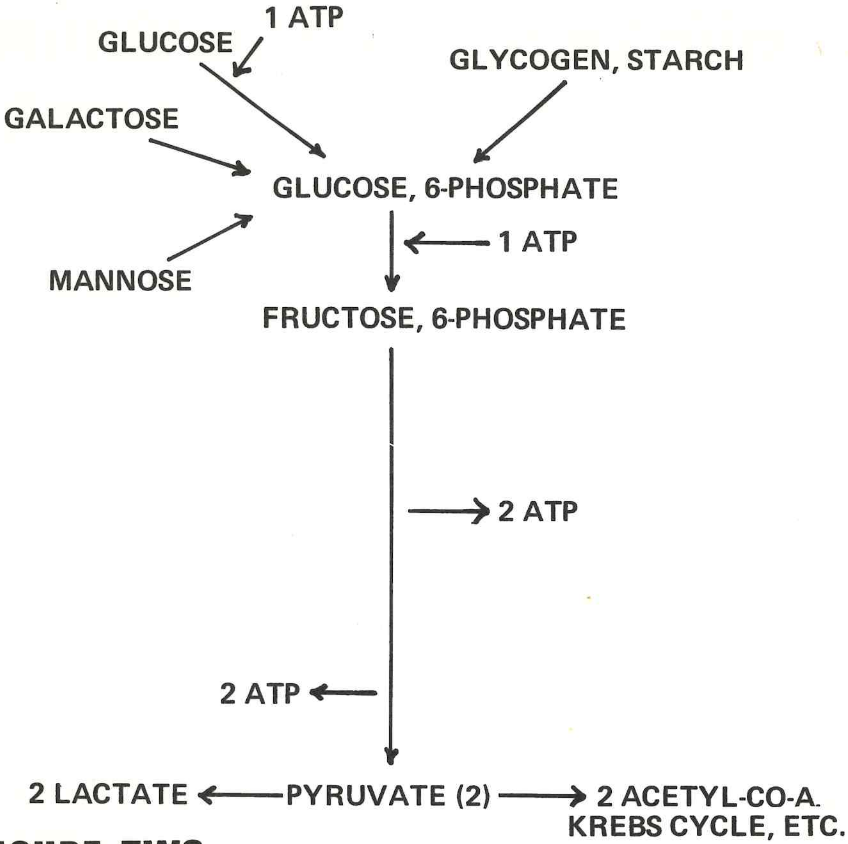


FIGURE TWO Glycolysis

Acetyl Co-A is an interesting molecule. It has several possible fates in the cell. Its major fate is to combine with one of the products of the Krebs Cycle, thus producing citrate (citric acid, the same citric acid we find in oranges, grapefruits, soft drinks, etc.). This reaction to form citrate is actually the first step in the Krebs Cycle.

Besides passing into the Krebs cycle, acetyl Co-A can function as the starting point for the synthesis of fatty acids, ketone bodies, and a variety of other important compounds such as cholesterol and many of the body's hormones (see Figure 3).

Most important to the runner is the production of ketone bodies by an excess of acetyl Co-A molecules. Just as we can use acetyl Co-A as the building blocks of fatty acids, so then is acetyl Co-A the final breakdown product of fatty acid degradation. Stored fats are broken down to fatty acids. Fatty acids are then broken down to acetyl Co-A molecules which can enter the Krebs Cycle, or can be used to synthesize a variety of compounds.

More than likely, the breakdown of fatty acids will produce more acetyl Co-A than can be processed via the Krebs Cycle or can be used in synthesis.

This excess will then be used in ketogenesis, or the production of ketone bodies. The ketones produced are not normally burned and will tend to build up in the cell, eventually resulting in a physiological state called ketosis.

In running long distances, our bodies rely as much as possible on carbohydrate metabolism for the needed energy. However, as the run proceeds, we begin to deplete these carbohydrate stores. This results in a gradual increase in the metabolism of fatty acids as a source of energy. Towards the end of a long run, we may have used up nearly all of our stored carbohydrates (see Figure 4). This means that the majority of our energy demands are being met by the breakdown of fatty acids to acetyl Co-A, which is then "burned" via the Krebs Cycle and the ETS.

Fatty acids are rich in energy—much more so than carbohydrates, to yield the same amount of energy. But more importantly, the cell cannot use all the acetyl Co-A produced by fatty acid breakdown. So some degree of ketogenesis will result. If we are using mostly fats, as we are near the end of a long run, then an abundance of ketones will be produced, resulting in ketosis.

The effects of ketosis are known to the majority of distance runners. Ketone bodies cause an increased acidity of the body's fluids, much the same way lactate does. And the results are similar: cramping, listlessness, muscular weakness, etc., to the point where the muscles will either "lock up" or cease to function. Sound like the "20-mile blues"?

So although we can depend on fatty acids for energy when our carbohydrate supply is low, they are a poor substitute. The end results will be grossly uncomfortable, to say the least.

KREBS CYCLE AND E.T.S.

Whether we use fatty acids or carbohydrates for energy (proteins can also be burned, but they are significant only in starvation situations), oxygen is essential to ATP production beyond glycolysis. These oxygen requiring processes are sometimes referred to as aerobic respiration, or simply respiration.

The first step in respiration involves the oxidation of the end products (pyruvates) of glycolysis to acetyl Co-A. From here, the acetate portion of the acetyl Co-A molecule enters the Krebs Cycle by combining with another molecule to form citrate (hence the synonym citric acid cycle). This is the first step in the Krebs Cycle.

As the acetate molecule (mounted in citrate) passes through the Krebs Cycle, it is enzymatically degraded. At the end of the cycle, all that remains of the acetates (and thus the original glucose) are a few carbon dioxide molecules and hydrogen atoms.

The carbon dioxides we can dispense with. They pass out of the cell and are transported on the hemoglobin of the red blood cells to the lungs, where they are exchanged for oxygen molecules.

The hydrogen, however, has a more significant fate. As the Krebs Cycle proceeds, hydrogen atoms are released at certain stages. These hydrogen atoms (and their corresponding electrons) are transported to the machinery of the electron transport system. The ETS consists of a chain of molecules which act as carriers.

The electrons (from the Krebs Cycle via hydrogen) are handed down the chain from carrier to carrier until they reach oxygen, which is the final acceptor of the electrons. The oxygen, upon accepting the electrons and hydro-

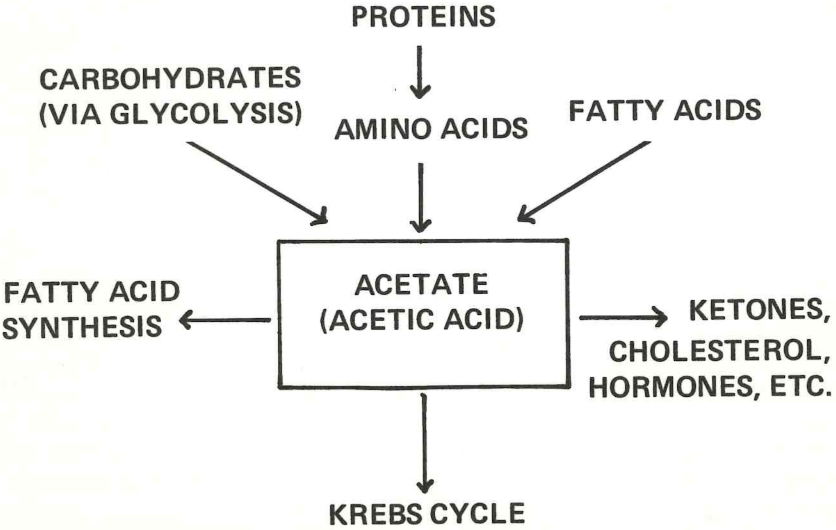


FIGURE THREE Origins and Fates of Acetate gens, forms water. This water, along with the carbon dioxide, is the final product of the process which began with glucose.

As the electrons pass down the line to oxygen, they are also passing from a higher to a lower energy state. Therefore, energy is released as the electrons pass from one carrier to the next. This energy is used to drive the bonding of phosphate to ADP (adenosine *di*phosphate) to make ATP.

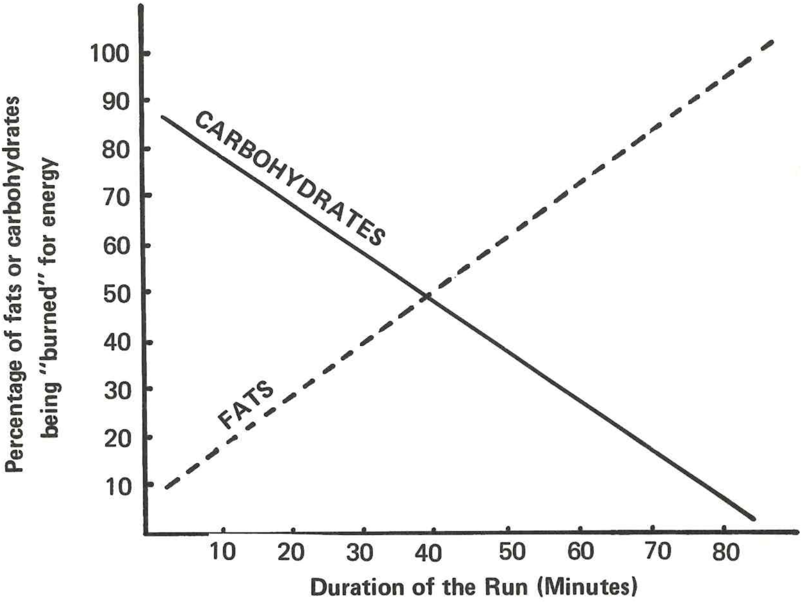


FIGURE FOUR Utilization of Fats vs. Carbohydrates as Compared to Running Time. (Costill, 1968)

Thus the energy which was released from the breakdown of the acetates (and hence from glucose) was "held" in the electrons which were passed into the ETS. As these electrons were transported through the ETS, they released their energy. This energy was then used in the bonding of phosphate to ADP to form ATP. In other words, the energy from the oxidation of the original glucose molecule has been *conserved* in the bonds between phosphates and ADPs. The ATP thus produced is the "energy currency" of the cells. The energy stored in this third phosphate bond can be released where needed (such as in muscle contraction) by simply breaking the bond to form ADP and phosphate again.

This conservation of energy by the production of ATP molecules in the ETS is dependent on oxygen. If insufficient oxygen is present to accept the electrons at the end of the chain, then the effect is like having a wall at the end of a conveyor belt. The whole process will back up and the only ATPs produced will be those from glycolysis. This, you will remember, operates without oxygen.

But lack of oxygen is not the only thing that will block the conveyor belt. Many poisons—most notably cyanide and barbituates—act by blocking the flow of electrons down the ETS. Thus even though sufficient oxygen may be present, the electron flow is halted before oxygen and a similar stoppage occurs. We can see from this why barbituates are ill-advised preceding athletic events.

While on the subject of drug effects on cellular function, it might be interesting to note just how caffeine works in increasing energy production. Many long distance runners drink tea or cola drinks during a race. Both drinks contain either caffeine (in cola) or a substance closely related called theophylline (in tea). These substances once in the blood stream, enter various cells and

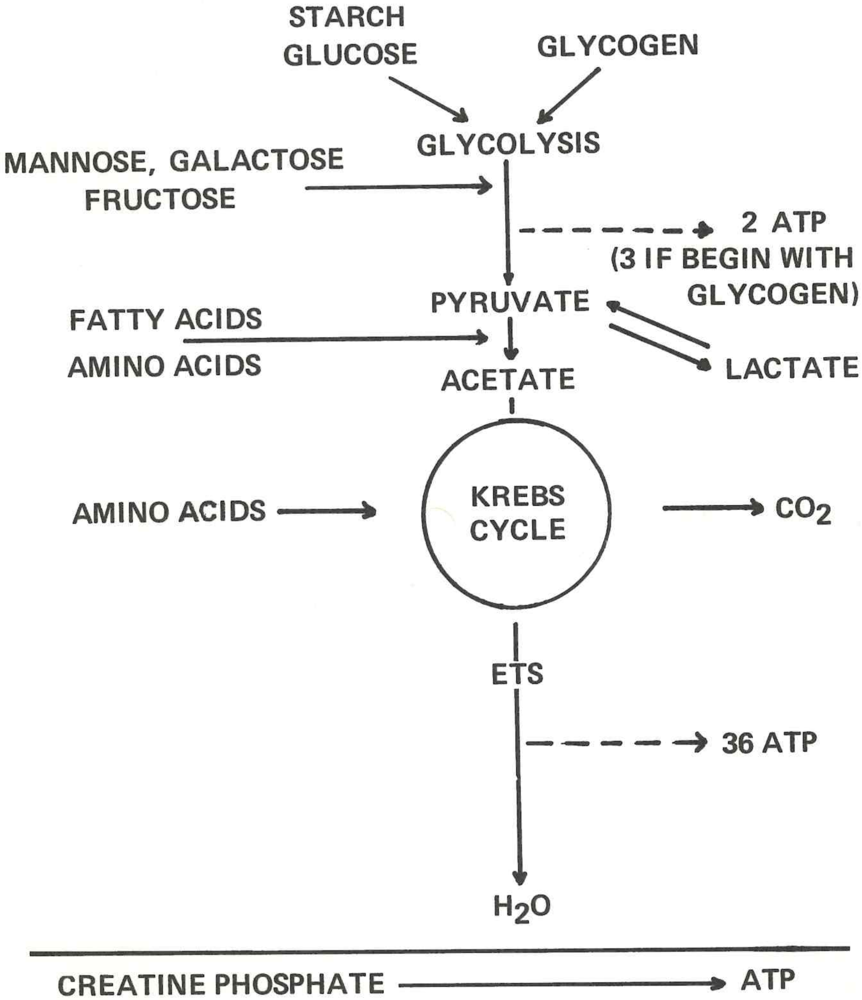
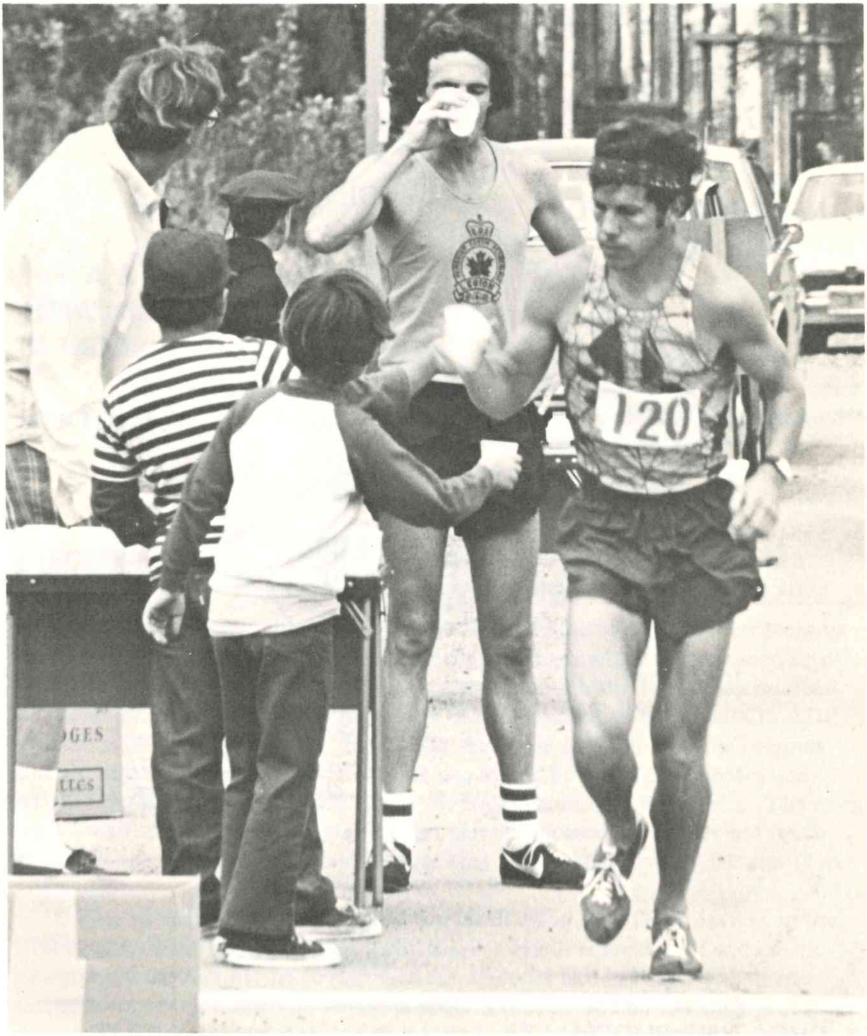


FIGURE FIVE The Different Ways in which the Energy Requirements of the Runner are Met.

stimulate the activation of the enzymes, which cause glucose units to be released from glycogen.

In addition, caffeine stimulates the release of fatty acids into the blood. Therefore, caffeine and related compounds make available greater quantities of "burnable" compounds. (It is interesting to note that adrenalin has an effect similar to caffeine on the release of glucose from glycogen.)

In this way, the distance runner is ensuring that he will have adequate fuel for both the initial stages of a race, where carbohydrates are important, and the later stages, where fats are more significant.



"The loss of excess body water can cause collapse. It is for this reason that almost all long distance runners will take in some liquid at points during a race." (John Marconi photo)

INTO THE BLOODSTREAM

In the process of extracting energy from foodstuffs, the blood and other body fluids play an essential role. Without them, we couldn't get oxygen to the tissues or get supplies of fuel substances. Wastes would build up, and soon we would have an upset in the all-important chemical balance in and around the cells.

All of the reactions of metabolism require very specific chemical conditions. Enzymes, for example, will completely lose their chemical integrity if the pH (acid-base balance) of the body fluids changes even slightly.

So, when lactate or ketones build up in the blood and cause the pH to drop (become more acidic) below normal levels, we begin to lose our ability to produce ATPs as well as other vital functions. The reason for this is that the enzymes of glycolysis, the Krebs Cycle, etc., are being slowly denatured by the more acid conditions and are gradually losing their ability to effect their respective reactions.

The blood is therefore not only important as a carrier of foodstuffs and oxygen, but as a regulator of the internal environment. The transport of oxygen, however, is perhaps the most important to the runner.

As we begin running, there is an immediate demand for more ATP molecules which are the direct energy sources of many body processes—most notably, in this case, muscle contraction.

To supply the initial energy to get us rolling, there is a slight surplus of ATPs and a small amount of readily available energy stored in muscle as creatine phosphate (CP). CP allows for the rapid production of ATPs within the cell without resorting to the standard processes (Krebs Cycle, etc.). It is an anaerobic energy source which is unfortunately limited. Only a few seconds of intense work can be performed using energy stored in CP. It is noteworthy that CP levels in muscle can be increased by anaerobic-type training, but only slightly. This may account for the training effect of increased "power" experienced by sprinters.

Regardless of how much of a training-induced increase in CP we have, it is still not adequate for anything beyond a sprint. For long duration exercise, oxygen must be supplied to the cells so that adequate ATP production can occur. Without it, we must rely on glycolysis to meet our energy demands. The pitfalls of this approach are familiar.

The body must then initiate physiologic changes to insure an adequate oxygen supply. What happens initially is that we have a rapid increase in the carbon dioxide level in the blood as the available oxygen is quickly used to "burn" the fuel within the cell. This increased carbon dioxide level triggers an increase in pulmonary ventilation (respiration rate), which exposes more oxygen to the blood coursing through the capillaries in the lungs.

As the blood, coming from the tissues via the heart, passes through the capillaries of the lungs, it gives up its waste cargo of carbon dioxide and takes on oxygen. This is accomplished by certain unique properties of hemoglobin.

Hemoglobin, the oxygen-carbon dioxide carrier of the red blood cells, has a greater affinity for oxygen than for carbon dioxide. In the oxygen-rich atmosphere of the lungs, hemoblobin will preferentially give up its carbon dioxide cargo for the available oxygen.

This does not explain, however, how the oxygen is unloaded once the hemogloblin arrives at the oxygen-starved tissues. The key to this exchange is myoglobin, and the special ability of hemoglobin to change its affinity for oxygen or carbon dioxide, depending on the relative concentration of the two.

Myoglobin is an iron-containing protein much like hemoglobin, but it is permanently situated in the muscle cells. It can bind oxygen more easily than hemoglobin. So when the red blood cells arrive at the capillaries in the muscle, the oxygen will tend to diffuse toward the myoglobin and from there into the mitochondria.

Myoglobin also acts as a storehouse of oxygen for the muscle cell. This means that even if an adequate amount of oxygen is *not* being transported to the tissues, aerobic respiration can continue for a short time by using the oxygen stored in the myoglobin. Over-distance and interval type endurance training increase the levels of myoglobin in the muscles. This expands the stores of oxygen and the enhances movement of oxygen from the blood through to the mitochondria, where the Krebs Cycle and the ETS take place. In this way, more oxygen is available for ATP production. As a result, muscles can contract faster and running speed is increased. This is just one of the many ways in which endurance training stimulates physiologic adjustments which improve fitness and performance.

Even without myoglobin's higher affinity for oxygen, a certain amount of oxygen would be unloaded by hemoglobin. Just as enzymes and the other chemicals of the body respond to changes in the internal environment, so does hemoglobin. Running requires increased energy turnover, via ATP production. The results of this increased production is an increase in temperature in the muscles, as a certain amount of energy is always lost as heat. Lactate production is also on the rise, and this along with a large carbon dioxide output makes the immediate environment more acidic.

All these factors cause a change in the oxygen-holding properties of hemoglobin. The greater partial pressure of carbon dioxide, coupled with drop in pH and an increase in temperature, make hemoglobin "want" to give up more of its oxygen than it normally would at rest. Normally, in a non-exercise situation, the partial pressure of carbon dioxide is higher than that of oxygen and a certain amount of oxygen is released. This is usually adequate to meet the demands of the situation. But when exercising, and thus needing more oxygen, the effects of exercise will cause hemoglobin to release more oxygen than it normally would.

Not only do exercise-induced changes cause the blood to give up more oxygen, but they also increase the blood's oxygen-carrying capacity. When exercise begins, fluids will tend to flow out of the blood to bathe the working tissues. This concentrates the hemoglobin in the blood so that a given volume of blood can transport as much as 10% more oxygen or carbon dioxide than it could at rest.

All these changes have the overall effect of enhancing the flow of oxygen from the air into the working muscles. This is essential for maintenance of the increased ATP output needed to perform the work of running.

DEALING WITH HEAT

An increased energy turnover brings with it the danger of heat stress. Body temperatures as high as 106 degrees (F) have been recorded at the end of a marathon, and temperatures over 104 are common. As pace and/or distance increases, maintaining a safe body temperature becomes a problem. The dissipation of heat is another important function of the body's fluids.

The blood and lymph serve to transport heat from the rapidly metabolizing muscle cells to the capillary networks close to the surface of the skin. It is here that the heat is dissipated into the atmosphere. This is seldom adequate, and other methods must be employed to ensure sufficient cooling.

Perspiration is the most important of these secondary measures. Water, drawn from the blood by the sweat glands, is released at the surface of the skin. If conditions are right, this water will evaporate and cool the skin and underlying capillaries. The lower the relative humidity, the more evaporation that will occur. If, however, the humidity is high, then little or no evaporation can occur. In this situation, the released water will remain in the liquid state and thus contribute little to the cooling of the blood.

Running on a hot, humid day brings with it the dangers of heat cramps, heat exhaustion and ultimately heat stroke. High atmospheric temperatures are dangerous enough, but loss of heat dissipation capacity which accompanies high humidity can result in a critical situation.

The wearing of bulky or constrictive clothing can produce a high relative humidity close to the skin and thus inhibit evaporation, even if the humidity of the atmosphere is low. It is a good idea to wear clothing which promotes the movement of water away from the skin such as a thin perforated nylon shell, or, in the proper place, nothing at all.

Even if clothing and conditions are ideal, heat stress will still be a problem. The problems of hyperthermia are much underrated by runners. In my estimation, no other single factor limits performance or endangers health to the degree that heat related stresses do.

Not only do we have to weather the adverse effects of high internal body temperatures, but also the problem of acute dehydration and electrolyte depletion. As running speed increases, sweat rates increase. In a race situation, approximately a quart of water is lost in one hour for each square meter of body surface area. This can mean a loss in excess of a gallon during a marathon.

The faster the pace, the hotter the atmosphere and the larger the individual, the greater is the rate of water loss. Weight losses as high as 13 pounds have been reported in marathon runners.

In a non-exercising situation where heat stress is a problem, water losses this large amounting to possibly 8-10% of the total body weight) would normally result in heat exhaustion. The reason for this is that the water which is lost comes from the blood plasma and causes a drastic reduction in blood volume. This circulatory stress does not occur during exercise, however. Fortunately, the large amount of water lost in exercise comes from the intracellular spaces and the volume of the blood is only slightly lowered.

Even though this unique adaptation offers some protection, it is not total. And eventually the loss of excess body water can cause collapse. It is for this reason that almost all long distance runners will take in some liquid at points during a race.

Admittedly, the amount of water that can be reasonably consumed during a road race cannot even begin to approach the large quantities lost. But even a small intake may be enough to keep hydration above the collapse level.

Even more important than replenishing fluid losses is the replacement of electrolyes (ions such as sodium, potassium, calcium and magnesium) which are lost in sweat. Runners seem to be well-adapted to high degrees of dehydration and high internal body temperatures. But the ravages of unreplaced electrolyte losses are felt by even the most fit.

Nerve function is dependent on the maintenance of specific concentrations of ions both on the inside and outside of the neuron. Muscles require calcium and a similar balance of ions for contraction and normal functioning. If this balance is upset, then their respective functions will be upset, possibly to the point of total collapse.

The cramps and decreases in coordination sometimes experienced in long runs are most probably the result of an upset in this delicate balance due to electrolytes lost in sweat. Certainly critical rises in temperature and low pH also influence the situation, but nothing has the rejuvenating ability of a glass of, say, ERG, on aching and cramped muscles.

The analysis of the sweat of distance runners reveals that larger amounts of potassium are lost than in the sweat of other athletes. This may account for the particular attractiveness of orange juice after a long run. It is high in potassium.

Other investigators have come to the conclusion that losses of ions are not significant with the exception of magnesium. In general, opinions are mixed, but almost all researchers will agree on the necessity of ingesting some sort of electrolyte solution during a race of more than an hour's duration.

Such concoctions as Gatorade, Actionade and the runner's favorite, ERG, have been developed to provide the proper concentrations of electrolytes in water for ingestion by dehydrated athletes.

Taking in water alone, or taking salt tablets without adequate water, is counterproductive. Either way you are aggravating the existing balance by adding too much of one component of the system without the others. Even though you may experience immediate relief, you are in effect hastening the onset of collapse.

Experience and a number of scientific studies have produced a set of guidelines for replenishing water and electrolyte losses.

- Drink a solution of electrolytes in water which is designed to replace sweat losses.

- Drink often and begin drinking as early in the race as possible. Though international rules prohibit fluid intake before the first 10 kilometers are completed, it might be wise to ignore this rule where plausible. Some runners have reported no discomfort in drinking a 12-ounce glass of electrolyte solution immediately before running.

- The fluid ingested should be as close to body temperature as can be tolerated. Cold drinks may cause gastric upset when taken on an exercising stomach.

Although a broad selection of professional quality electrolyte replacement drinks are available, a situation may arise where it is not possible to purchase the above. In that case, the following drink may be mixed from commonly available household items. This drink is designed as a substitute and should supply the required electrolytes in their proper concentrations, although not with the accuracy and consistency found in the commercial drinks:

(1) Mix up 1½ quarts of orange juice in a two-quart container. (2) Add one-half teaspoon of table salt and one-fourth teaspoon of baking soda. (3) Add water to bring the total volume up to two quarts. (4) Thoroughly mix contents before ingesting.

Some individuals may wish to add magnesium. In this case, a 250-milligram tablet of Dolomite may be ground up and mixed in. A four-once serving (minus the Dolomite) will supply *approximately* the following: sodium (75 mg.), potassium (120 mg.), chloride (110 mg.), 36 calories and 36 mg. vitamin C.

Chapter 2

THE CHANGES

"We should approach running not as if we were trying to smash our way through some enormous wall, but as a gentle pastime by which we can coax a slow continuous stream of adaptations out of the body." (George Beinhorn photo)

ADAPTING TO EXERCISE

Adaptation is a function of stress. A certain type, intensity and duration of stress will produce a corresponding adaptation. We are accustomed to viewing the physiological adjustments accompanying prolonged exposure to cold, heat and high altitude as adaptations, but few think of endurance training as an adaptation-producing stressor. This concept is the key to understanding the changes in body function brought on by running.

If we view the various types of training we employ as stressors, we can, by controlling these stressors, determine the type and degree of physiologic adaptations which we will undergo. This type of approach is helpful in avoiding injuries as well as in achieving optimal results.

Too much of a particular stress will produce a breakdown. This is the natural response to excessive stress and is itself an adaptation of sorts. Total breakdown of a system incapacitates it and prompts physiological responses which contribute to healing and refilling of the drained reservoir of "adaptation energy." By applying the stresses of training judiciously and by listening to the messages your body is sending you, overloads can be avoided. And in the same way the stress load of training can be adjusted to optimal levels.

Tom Osler in the *Encyclopedia of Athletic Medicine* has compiled a list of danger signs which indicate an overstressing of the body:

1. *Mild leg soreness.*

2. *Lowered general resistance (evidenced by sniffles, headaches, fever blisters, etc.).*

3. *Washed-out feeling and I-don't-care attitude.*

4. *Poor coordination (evidenced by general clumsiness, tripping, stubbing one's toe, poor auto driving, etc.).*

5. *"Hangover" from previous run.*

Dr. George Sheehan has added another list of signs in the same publication:

Objective signs: *Performance–Sudden drops in the ability to handle distances or paces. Weight–Drastic drops in weight–say, several pounds in a day or two. Pulse–Significant increases in normal resting rate. Breathing–anaerobic (forced breathing) running begins at a considerably slower pace than normal. Elimination–Any major deviation from the normal schedule of urination and defecation. Sleep–Extreme difficulty in getting to sleep, or staying asleep (particularly the latter).*

Subjective signs: *Pain–Perhaps the most single important warning sign. Pains in the muscles, joints and tendons are the most common. Pains that increase while running are more serious than those which gradually diminish in the course of the run. Illness–Frequent colds, sore throats, headaches and stomach upsets. Fatigue, nagging tiredness that lingers long after runs are complete, and carries over from day to day. Appetite–disinterest in eating. Thirst–Insatiable craving for liquids, which is often a sign of chronic dehydra-*

tion. Psychological Resilience—A mixed bag of symptoms including lack of enthusiasm or confidence, inability to relax, irritability, etc.

In essence, we must cultivate an awareness of the body. People are generally unaware of their general state of health, and are more tuned in to the sensual aspects of living: tastes, appealing visual stimuli, drug-altered feelings of well-being (from coffee, colas, cigarettes, marijuana, etc.). These sensations hide the truth, often until it is too late. Every day, people walk into hospitals for general checkups and are informed they have a tumor the size of a grapefruit in some major organ. They were unable to see through the haze created by ubiquitous external stimuli. The messages that their bodies sent fell on deaf ears.

Cultivating this sensitivity is a most difficult process. We are so practiced in the art of experiencing the outside world that learning to listen to the voices from within becomes a monumental task. Perhaps the easiest way to begin is to set up a continuous flow of biological feedback. This is generally what Sheehan and Osler are advocating.

They are saying, "Look at yourself, look at your weight, pulse, breathing, etc., and look for signs of excessive stress or imminent breakdown." To accomplish this, we must have a daily input of physiologic data. The obvious first step in this program is a training diary, and not just a mileage chart.

Upon rising, take your resting pulse and record it. Taking if for a full minute or longer is preferable to the short "10 seconds and multiply by six" method. Record your weight also, before breakfast. Note your resting respiration rate (number of breaths per minute). How many hours did you sleep? Was it a good sleep? How many times during the day did you defecate, urinate? Anything unusual (large flow, unusual color, etc.)? How far did you run? How did you feel? Good, bad? Record your impressions. Write a short daily report of your general state of health.

This daily monitoring of many of the body's functions will provide you with an objective framework on which to judge your general state of health. You will soon become increasingly aware of "where you are at" physically and emotionally. In this way, you will be better equipped to judge the effects of your running (and also the multitude of other stresses encountered in a day).

Without this constant feedback, however, the mind will tend to distort things and force an emphasis on the performance-related aspects of running. That is not to say that performance evaluation is at all a basically negative pastime. Quite to the contrary, a constant evaluation of your performance capacity is one of the best measures of health, when considered with the other variables. The best measure of performance capacity in endurance-requiring activities is the maximum oxygen consumption. (The appendix contains directions for a self-administered test which will give an estimate of your maximum oxygen consumption rate.)

A weekly report of your maximum oxygen consumption rate as estimated by the suggested test will provide a constant monitoring of your progress in training as well as another sign of overstressing.

Many of us approach running as a goal-oriented pastime. This is all well and good if the demands of the body are obeyed. In the long run, cultivating a body awareness and obeying the signs which this awareness reveals will allow us to achieve the same (probably better) level of performance, without damaging the body and mind.

In essence, we should approach running not as if we were trying to smash our way through some enormous wall, but as a gentle pastime by which we can coax a slow continuous stream of adaptations out of the body. It is the physiologic enhancement provided by these adaptations that will allow us to improve performance, *not* the strength of will, which forces us through pain and suffering. Too much is made of will-power, desire, etc., in athletic literature. It is a false impression perpetuated by a school of naive journalists bent on image-making and unaware of the tremendous scope and complexity of the process of endurance training.

By heeding the warnings of the body and by understanding the nature of adaptation, we can progress in our enjoyment of running by slowly raising our level of fitness.

OXYGEN CONSUMPTION

Having realized that training effects are adaptations, and that training itself provides the stress which induces these adaptions, we can proceed in an exploration of some of the physiological changes which constitute the phenomenon we often refer to as "getting in shape," or "training." Although these adaptive changes certainly have their magical component, we do not magically become fit. There are a series of basic alterations in the structure and function of the body's various systems. These alterations allow us to cope with the stresses applied by mile after mile of continuous running, or a carefully applied interval program.

If we were to look at a list of all the physiologic changes brought on by endurance training, one observation would become immediately apparent. The vast majority of measurable changes are in the various components of the oxygen-transport system and in the respiratory chemicals (enzymes and ETS carriers) of the cell which account for the utilization of oxygen. These changes reflect a basic increase in what is called cardio-respiratory fitness. This type of fitness is an expression of the body's capacity to take oxygen from the atmosphere, to transport it to the tissues (especially the working muscles) where it is used in APT production, and to remove the carbon dioxide produced by this process and release it to the atmosphere.

Since the limiting factor for this whole system is oxygen, we can evaluate its functional capacity (i.e., a person's cardio-respiratory fitness) by measuring how much oxygen is consumed while performing maximal work. This figure is refered to as maximal oxygen uptake or the maximum oxygen consumption rate. The laboratory techniques used to measure this capacity are described in the appendix. The techniques and equipment required for accurate measurements are extremely sophisticated. However, you don't need $10,000 worth of equipment to approximate your level. Dr. Kenneth Cooper proved that.

The now famous Aerobics program was the first major popularization of the basic tenets of cardio-respiratory fitness. Just as heroin addicts are supposed to have started with marijuana, many running addicts will confess to having started with Aerobics.

The 12-minute run or the 1.5-mile run are actually indirect measurements of maximum oxygen consumption rate. Extensive laboratory tests have established a high correlation between certain oxygen uptake values and the distance one can run in 12 minutes or the time it takes to run 1.5 miles. From these measurements and an enormous quantity of data, Cooper has established various fitness levels based on oxygen uptake values as indirectly measured by either of the two tests.

Just to make things interesting, why don't you take the time to estimate your maximum oxygen consumption rate. The Cooper tests are covered in his books, and another self-administered test is outlined in the appendix.

Once you have this value, you know a little more about yourself. You know how much oxygen you can consume maximally and you have some idea of how fit you are. But this value tells you much more than that.

Indirectly, you have measured the capacities of a number of bodily functions:

- The rate at which the lungs can take in and exhale air, and the volume of air that can be handled in a given time.
- The oxygen-carrying capacity of the blood.
- The ability of the heart and peripheral circulatory system to transport this oxygenated blood to the tissues.
- The capacity of the blood to give up, and of the tissues to bind, oxygen once it is delivered.
- The capacity of the individual cells to utilize this oxygen to produce ATPs.

If your estimated maximum oxygen consumption rate is below 40, then most if not all of the above capacities are below the levels they should be. If there is indeed comfort in numbers, then you shouldn't feel too badly, because the majority of Americans will fall into this category.

The spectrum of fitness is vast. At one extreme we have the cross-country skiers and distance runners with values above 80 milliliters of oxygen consumed per kilogram (2.2 pounds) of body weight per minute. At the lower extreme, we find the individual with the well-trained digestive system basking in the blue light of his TV set. If we could somehow drag him away from his TV (perhaps during the soap opera period in the afternoon) and test him, he might score as low as 25 ml./kg./min.

No amount of training would allow this individual ever to achieve the superlative values of trained endurance athletes. However, if we could somehow perform the miraculous and convince him to jog a 1½ miles or more several days a week for a number of weeks, we would observe an increase of as much as 20% in his oxygen intake value. If a weight-reduction program were to accompany his jogging, then the values would be considerably higher.

What we have done is to apply a daily dose of stress to the various functions of the cardio-respiratory system, as outlined above. The result of this stress has been a series of adaptations which have allowed the body to consume more oxygen.

- Lungs are stronger and can move more air in and out at a faster rate.
- The blood can carry more oxygen.
- The heart has grown in size and becomes a more efficient pump.
- There are more blood vessels in the working tissues allowing for more extensive transport of oxygen and food materials.
- The tissues themselves can bind more oxygen for use in aerobic metabolism.
- The machinery of aerobic metabolism is more extensive, allowing for a greater utilization of the oxygen supplied.

These adaptations can be viewed in two categories: as enhancements of the oxygen transport system, or as alterations in the respiratory capacity of the cells.

OXYGEN TRANSPORTATION

The lungs of the trained runner are able to process a larger volume of air than the untrained individual's lungs. The vital capacity of the lungs is the maximum volume of gas that can be exhaled from the lungs following a maximum inspiration. As such, this capacity reflects the volume of the lungs and the strength of the respiratory musculature. As you would expect, runners have much greater vital capacities than normal. Nearly six liters of air can be processed in a single breath by the average trained distance runner, whereas the untrained person has a vital capacity of less than five liters.

Even more important to the runner is the maximum breathing capacity. MBC measurements demonstrate the maximum amount of air that can be moved in and out of the lungs over a period of time. MBC values for normal male subjects usually fall within the range of from 125-170 liters per minute. Figures of greater than 210 liters per minute are not uncommon for distance runners. This reflects the greater strength of their respiratory muscles, as well as their large vital capacities.

But even a large MBC is not significant to the runner without the capacity to sustain a high percentage of his MBC over long periods of time. David Costill, the noted exercise physiologist from Ball State University, has observed highly trained distance runners breathing over 120 liters per minute for more than 20 minutes!

Moving large volumes of air in and out of the lungs is rather pointless if the blood does not have a correspondingly greater capacity to extract the oxygen and transport it. The lungs provide a place where the blood, in extensive capillary networks, can come in contact with the atmospheric air and its precious cargo of oxygen. There is so much oxygen in the lungs that when the carbon dioxide-loaded hemoglobins (contained in the red blood cells) pass through the pulmonary capillaries, they give up their carbon dioxide and take on oxygen. The trained runner has more red blood cells and more hemoglobin in each of those cells than does the untrained individual. This amounts to a greater capacity to pick up and carry oxygen.

Once the blood is saturated with oxygen, the blood must be rapidly and efficiently pumped through the blood vessels to the capillary beds in the working tissues. To accomplish this, the heart has grown in size and the blood vessels supplying it have developed to increase the oxygen supply to the cardiac muscles. Since the volume, musculature and oxygen supply to the heart have been thus increased, we would expect the pumping capacity of the heart to increase. Such is the case. The volume of blood which can be pumped out of the heart with each beat (stroke volume) is almost doubled (nearly 200 milliliters, average) in trained persons as opposed to less active individuals of the same age group (between 100 and 125 ml.).

This explains the low resting pulse rates common among distance runners. If the body requires a certain amount of blood and the heart can pump much more per beat than it could before training, then it stands to reason that it needs to pump fewer times per minute to supply the same volume of blood. This same pattern persists as the work load increases. At the same work load, the heart of the runner pumps fewer times per minute than the untrained person.

Because of this decrease in heart rate at rest corresponding to an increase in stroke volume, we see no net increase in cardiac output (liters of blood pumped per minute) *at rest*. However, when performing maximal exercise the trained runner's heart can pump 35-40 liters per minute compared to 20-25 liters for the untrained heart.

The increased strength and power of cardiac muscles are well demonstrated in these dramatic changes. But what about endurance? What good is a large maximal cardiac output if only a small percentage of it can be sustained for long periods of time? In the category of sustained output the runner's heart is nothing short of phenomenal.

In *Runner's World* (June '73), Dr. Joan Ullyot reported on the cardiac behavior of Ron Daws during a marathon. She found that he could sustain a heart rate of 177-180 beats per minute for the duration of the marathon. This is a whopping 95% of his maximum heart rate of 187. Since cardiac output and oxygen consumption are closely related to heart rate, we can assume that both of these values were correspondingly high as well.

These values indicate an incredibly efficient cardiac circulatory system. The vessels supplying the heart, as it pumps at such a high rate for so long, must be extensive to supply food substances and oxygen so efficiently. It is one thing to consider the energy requirements of a leg muscle which is contracting perhaps 75 times per minute, and quite another to comprehend the needs of cardiac muscle as it contracts at 2½ times that rate. The near impossibility of maintaining an adequate oxygen and food supply to a muscle with such a rapid contraction rate raises an interesting possibility.

The efficiency of normally functioning cells involved in energy transformations (the calories of energy stored in the bonds of ATP formed as compared to the calories of energy introduced in glucose) is usually estimated at between 40% and 60%. That is to say that up to 60% is conserved in ATP formation with the remaining lost as heat.

The wings of hummingbirds are capable of rapid contractions. They maintain this high rate of contraction by several special adaptations. One of these adaptations is the glycerol phosphate shuttle which allows for the recycling of certain components of respiration. This recycling allows the flight muscle of the hummingbird to be nearly 100% efficient. Reducing the loss of energy as heat reduces energy expenditure for heat dissipation and allows for almost total utilization of the food substances supplied to the muscle.

There is some suggestion that this shuttle may be in operation in human cardiac muscle. If this is indeed the case, then it would help to explain the phenomenal sustained rates of contraction which have been observed.

Although the oxygen supply problems of skeletal muscle are not nearly as critical as they are for cardiac muscle, the large amounts of oxygen demanded by the working muscles requires that the peripheral circulation expand to handle the load. This is, in fact, the case. Both the numbers of arteries leading to the muscles and the density of the capillary beds within the muscles are increased by training. This increase is proportional to the role that the muscle involved plays in running. The gastrocnemius muscle of the calf has been shown to increase its capillary density nearly 100% in response to a running program. As would be expected, the masseter muscle of the jaw showed no response to the training program. (The subjects used must not talk as much as I do when I run.)

Now that we have strong lungs and an efficient circulatory system to extract oxygen from the atmosphere and deliver it to the tissues, we are stuck with the problem of unloading this oxygen into the cells and getting it to the mitochondria where it is needed for ATP production. This is where myoglobin comes into play.

As we saw earlier, the changes in the cellular environment brought about by exercise cause hemoglobin to "want" to give up much of its oxygen and take on carbon dioxide. Coupled with this increased unloading is the strong affinity of myoglobin for oxygen. Myoglobin, the oxygen binding pigment of muscle, has six times more affinity for oxygen than does blood hemoglobin.

Endurance training raises the levels of myoglobin to nearly twice the normal levels. This means an increase in the muscle's capacity to extract oxygen from the blood and pass it on to the mitochondria. At the same time, increased myoglobin means an increase in the storage of oxygen in the tissues. While this increased storage is too small to be significant to the distance runner, in a mile or an 880 it may be important as it would delay the onset of lactate buildup.

What we have achieved so far is to increase the flow of oxygen from the atmosphere into the mitochondria. The mitochondria (often refered to as the powerhouses of the cell) are responsible for the aerobic energy metabolism of the cell. Each cell contains a number of these organelles. Each mitochondrion contains all of the enzymes, etc., needed for the Krebs Cycle and the ETS. The end products of glycolysis, the breakdown of fats and the breakdown of proteins, are all fed into the mitochondria, where they are aerobically metabolized to produce ATP molecules.

As mentioned earlier, ATP molecules supply the energy for much of the body's basic functions (movement, biosynthesis and internal transport). Without an increase in the production of ATPs, the body would be unable to maintain the levels of work capacity demanded by running.

The first step in ensuring a high ATP output is to see to it that the oxygen necessary for aerobic metabolism is delivered in sufficient quantities. The second and most important phase is to increase the machinery of aerobic metabolism so that the available oxygen can be utilized and more ATPs produced to meet increased demands for energy.

Since the rates at which the reactions of the Krebs Cycle and the ETS can take place are under careful control, the only way to increase energy production is to have more mitochondria and more of the chemicals needed for ATP production. Endurance training increases the number and size of the mitochondria of muscle cells. Along with this goes a well-documented increase in the enzymes of the Krebs Cycle, and the enzymes and other chemicals of the ETS.

The net effect of these increases is that the cell can utilize more of the oxygen supplied to it, and can produce more ATP molecules. This means more rapid contractions of the muscle are possible before anaerobic conditions are reached. The end result is a general increase in work output, which means faster times and less pain.

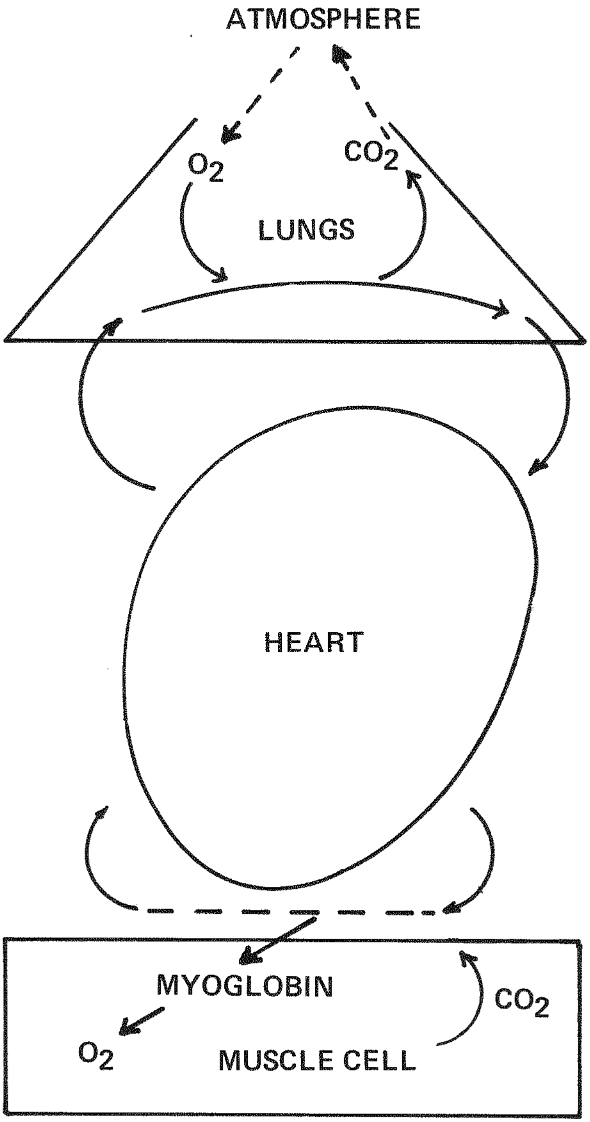


FIGURE SIX Oxygen Transport to the Muscle

PRACTICAL APPLICATION

David Costill of Ball State has shown that there is a poor correlation between maximum oxygen consumption rates and marathon running times. This is contradictory to what one would expect. Certainly it is important to have a fairly high oxygen intake rate to be able to run a marathon. What Costill has shown is that among *trained* runners the limiting factor is not the maximum oxygen consumption rate. Instead, he suggests that the limiting factor may be the ability to sustain a high percentage of that rate for prolonged periods. He cites Derek Clayton as a prime example. Clayton has only an average oxygen consumption level (69.7 ml./kg./min.) but can sustain 84% of that total for long periods of time. Other marathoners with values of 78 ml./kg./min. could sustain only 64% of their total for long periods of time.

This information, when compared to the fantastic output maintained by Ron Daws, indicates that the limiting factor is not the transport of oxygen to the tissues but the ability of the metabolic machinery of those cells to use a high percentage of that available oxygen to produce ATPs and to sustain that level of utilization for long periods.

Once an individual has achieved a fairly high maximum oxygen consumption rate, he is limited in his performance by the mitochondria and the concentrations of the chemicals which constitute the machinery of aerobic metabolism. This concept has great value in designing a training regime.

While it is important to do some speed training to develop coordination and efficiency of movement, it is the long, slow continuous type of training which produces the most beneficial adaptations for long distance running. In training for distance running, one can choose either intensity or duration. We can choose to run a few miles at an intense rate, or we can choose to run long distances at a slower pace. Either method will produce an enhancement of the physiologic factors determining oxygen intake. But is this all we are after? Several factors must be considered.

High intensity workouts carry more of a danger of overstressing than do slower, more relaxed paces of LSD (long slow distance) type training. Also, as was pointed out earlier, it is the capacity to *sustain* energy output for long periods which we are after. It is better, then, to apply the stresses of long duration runs as opposed to shorter, more intense work. It is these prolonged stresses which best mimic the race situation. It is a question of *how long* we can sustain a given output and not how great an intensity we can achieve.

Also, the stresses of high body temperatures, acute dehydration and electrolyte imbalances are produced in longer duration runs. This allows the body to make adjustments in response to these particularly critical stresses.

I visualize the super distance runners of the future as training in special shock absorbing shoes, on surfaces prepared to reduce road shock to the joints and tendons. These runners will necessarily be full-time athletes as their weekly mileages will exceed 200 miles. They will be constantly monitored by a team of physicians, physiologists and biochemists in an effort to coax the maximal degree of adaptation out of the body.

As distasteful as this concept is to a fun-runner such as myself, these are the realities of international politics. The Russians are approaching the physiologically monitored running machine right now, and it should not be long before the rest of the world follows suit.

In a sense, it is a shame that the great body of knowledge concerning the physiology of running goes unused by the majority of the world's runners. The trial and error method can take one a long way, but who knows the potential of a runner armed with the knowledge of a thousand dedicated scientists. The Indians thought the white man was foolish with his fire spitting sticks, and rolling wagons... Knowledge is strong medicine.

"It is the capacity to SUSTAIN energy output for long periods which we are after. It is better, then, to apply the stresses of long duration runs as opposed to shorter, more intense work." (Steve Sutton photo)

Just how much do physiologists know about different styles of training? What are the effects of one type versus another? Which is more effective as a training tool? Is weight training beneficial? What are the physiological effects of altitude training and carbohydrate loading?

Research to date has not shown any one training method to be generally superior over another, provided the work load is constant. All four common types of training (interval, fartlek, continuous fast running, LSD) can produce improvements in cardio-respiratory endurance.

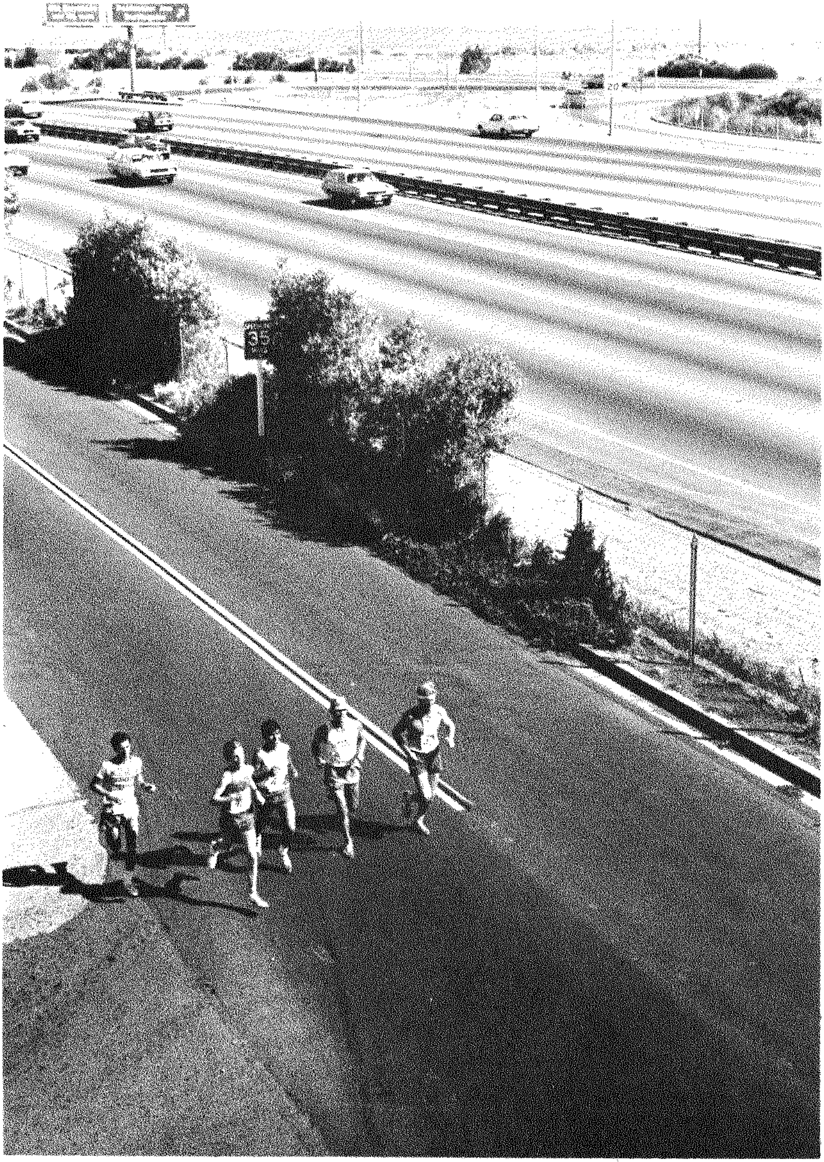
However, each type of training has certain special effects which should be considered in designing a training program. The interval and fartlek types of training are superior in neuromuscular training effects. Neuromuscular training increases coordination and results in more economy and efficiency of movement. Training exclusively at speeds slower than race pace will not have this effect. Thus, to maximize your gains, an occasional bout of speed-type training is recommended.

In the long run, however, long continuous runs (if of great enough intensity and/or duration) will provide the desired enhancement of cardio-respiratory endurance. For reasons of potential stress-related injuries, the longer and slower LSD-type of training is recommended. However, for optimal training effects, this type of running should be of extremely long duration. As the duration of a training run increases, there is a gradual increase in heart rate at a given pace. It is this gradual increase and related factors which optimize training effects.

In the light of this, one should not find it necessary to run a certain number of miles in a day but instead should concentrate on running for a certain length of time.

As to pace, the "talk-test" is a good yardstick for measuring pace in long slow runs. It would be interesting to see a study which would show the maximum work/output that would still permit conversation. In any case, in the absence of a friend (and not wishing to be caught talking to oneself), pulse rate is another good governor. Maintaining a pulse rate of *at least* 130 is sufficient to produce the desired effects (pulse during a run is best taken at the neck, for 15 seconds and multiplied times four). A pulse rate nearer to 150 will produce the same adaptations at a faster rate. However, when we consider the increased stress to the skeletal system, tendons and muscles at this increased pace, great care must be taken to avoid injury. My personal choice is to opt for the slower pace and to run longer.

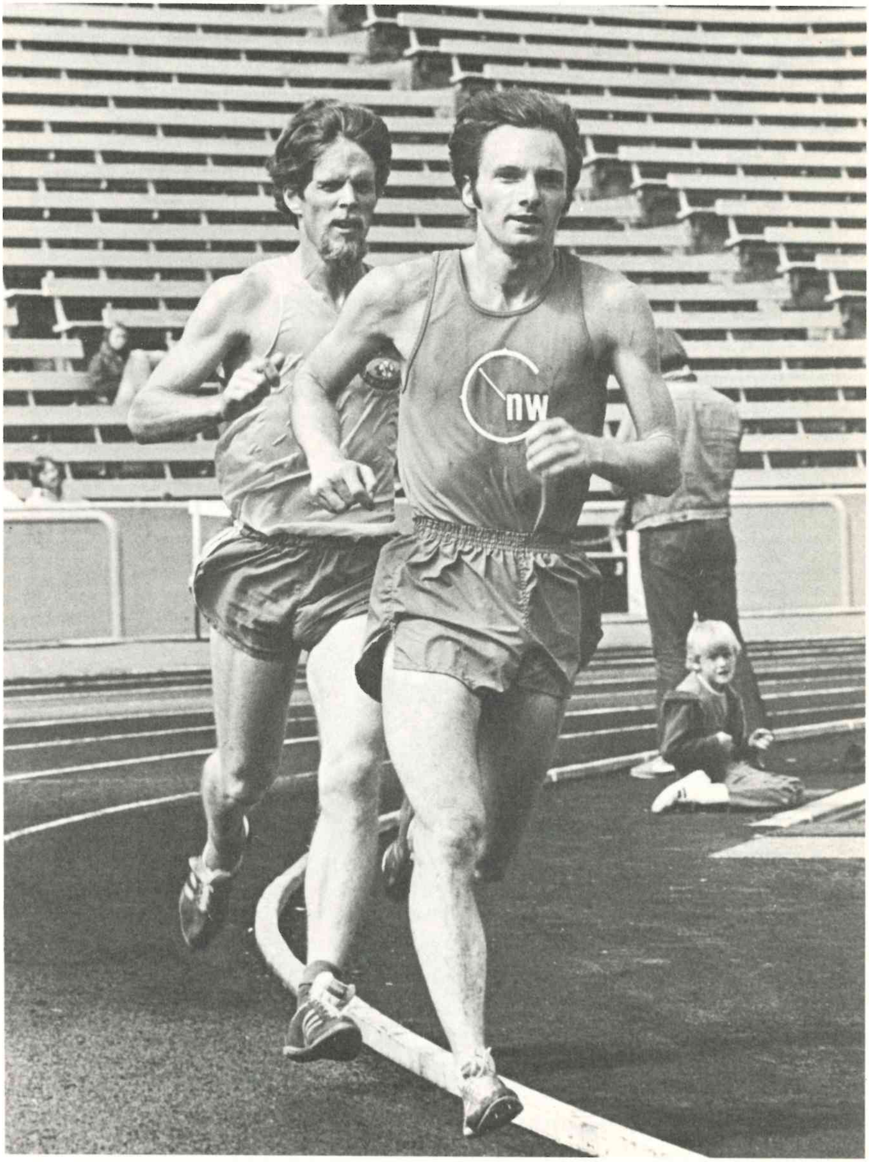
The training scheme of Tom Osler, as related in *The Conditioning of Distance Runners*, combines the techniques of fartlek and slow continuous running with a healthy dose of caution. Osler is aware of the pitfalls of overstressing. As a result, he has built into his training regime a series of checks and balances designed to allow the body sufficient rest and thus to avoid stress related injuries. The injury-plagued runner, or the new runner looking for a system, might do well to consider the "Oslerian" techniques. His emphasis on body awareness, his built-in flexibility and his understanding of the physiologic "needs" of the runner provide a broad foundation on which to build a personal training system.



"Research to date has not shown any one training method to be generally superior over another, provided the work load is constant. (Dale McKinnon photo)

Chapter 3

THE RESULTS



"The man has met his match. And, as always, his greatest adversary looms from within." (Jeff Johnson photo)

PHYSIOLOGY OF RACING

The race begins long before the run. Apprehension and fear cause the release of adrenalin (epinephrine). Blood floods the muscles, leaving the skin and vital organs. The stomach feels weak and light. The muscles reach supernormal levels of excitability and contractility. The heart beats faster and each beat causes a more complete emptying than normal. Respiration rates increase, loading the blood with oxygen. The brain becomes intoxicated with the increased oxygen flow. We feel light-headed, weak.

The warmup helps to stretch the tendons and muscles that will shortly be working overtime. Body temperature slowly rises to optimal levels. The oxygen transport systems are "loosening up," allowing for a more rapid increase to operating levels when the time comes. Myoglobin loads up with oxygen. The body is ready, poised on the brink. The energy transforming processes and oxygen transporting systems wait like a million tons of water behind a dam, ready to flood the body with oxygen and energy.

The gun sounds. The dam breaks. Myoglobin empties its oxygen into the mitochondria. ATP production climbs to meet the demands of rapidly contracting muscles. Soon the oxygen is gone. Creatine phosphates are converted to ATPs. Glycolysis starts spinning like a tire in mud, cranking out ATPs and spitting out an overload of lactates. The blood pH drops. Carbon dioxide levels climb.

The heart and lungs are already jamming for all they are worth to compensate for the rapid drop in oxygen levels in the tissues. But it takes time, about two minutes to be exact, to build the oxygen level back up from the near "empty" state into which it was thrown by the shock of accelerating from a standstill to at least 10 miles per hour. These two minutes of mostly anaerobic work are what produce the famous "oxygen debt."

Presumably the lactate that accumulates (while the body quickly raises its oxygen transporting capacity to catch up with a metabolism that has increased several-fold) in these first few minutes is maintained as a "debt" that must be repaid at the end of exercise. In reality, this is not the case, though it may seem so. All runners, regardless of distance, have to weather this initial anaerobic period. In marathon runners, the lactate that builds up during these first minutes is quickly oxidized. They will show very low levels of lactate during a race. However, towards the end of a race, increases in pace, fatigue of the oxygen transport system, or a variety of other factors may cause a slight lactate buildup. This may be considered as an "oxygen debt," which is gradually repaid during the period of continued high respiration and heart rate immediately following the run. In any case, the concept of oxygen debt is not as simple as it once seemed. But the term is an acceptable way to communicate a certain phenomenon.

The body does indeed have a debt to repay at the cessation of exercise. The oxygen content of the body must be refilled. Lactate and creatine phosphate residue must be oxidized. The metabolism of the body is increased due to adrenalin and elevated temperature. The body must work to lower its temperature to normal levels. Also, as the metabolism is elevated, the heart and muscles of respiration demand large amounts of oxygen. All these factors combine to effect what we refer to as repayment of the oxygen debt.

Back to borrowing it, though... Once heart rate, cardiac output and respiration rate have stabilized and can handle the oxygen demands of the working tissues, we settle into steady state exercise. From this point on, the months of training (or lack of such) will begin to show. Your ability to maintain a certain pace will depend on how well your body is adapted to tolerate the stresses it will encounter as the miles build up.

The first few miles always seem easy. The body is well hydrated and body temperatures stay within tolerable limits. Electrolytes have not started to go out of balance. Oxygen flows easily from the lungs through the circulatory system to supply the cells with abundant oxygen. Glucose molecules are popping off of glycogen and tumbling through glycolysis, the Krebs Cycle and the ETS. ATP production is adequate and well within the limits of the oxygen supply. Gradually, the nerves acquire an acupuncture-like anaesthesia. Your oxygen-enriched brain tells you you're feeling good. Your mind might come "unglued" from the numbed body for a moment, giving you the sensation of being "along for the ride." This transcendent euphoria is all too temporary, however.

Slowly, the water loss due to perspiration crosses the critical 3% level, and the discomforts of acute dehydration begin to build up. Body temperature rises to pull you down from your short respite from the limits of the body. The electrolyte balance begins to shift, imperceptibly at first. Your coordination and mechanical efficiency begin a slow decline.

Carbohydrates stores are gradually being depleted, thus contributing less and less to ATP production. The utilization of fatty acids is on a corresponding increase. All too soon you will reach the critical level where fatty acid metabolism is beginning to produce ketone bodies. If you loaded up on carbohydrates, the point at which this level is reached can be significantly delayed, even avoided in shorter runs.

The mechanism of carbohydrate-loading diets has yet to be determined. There are, however, several deductions which can be made from what is known. The usual timetable followed is to:

- Run to exhaustion one week before the race for which you are "loading."
- Eat no carbohydrates (only fats and proteins) after that run and for three days following it.
- Then, after this initial period of carbohydrate starvation, you reintroduce carbohydrates into your diet in large quantities (while still maintaining protein and fat intake).

This system is capable of nearly doubling your storage of glycogen in the muscle cells, if performed conscientiously. The enzymes that control the production of glycogen from incoming carbohydrates are controlled by the level of glycogen in the muscle. When glycogen levels are low, these enzymes increase in activity. Presumably, a prolonged period of low muscle glycogen causes a "super compensation" by these enzymes. Thus, when carbohydrates are reintroduced into the diet, they are quickly turned into glucose in preference to most other possible fates. The activity of these enzymes is so great that the cell is capable of storing much more glycogen than it could when normal enzyme activity exists.

The increased stores of glycogen mean extending your performance limits, as the discomforts of the ketosis accompanying fatty acid metabolism are postponed. This is not the only problem that is surfacing, though. Compared to the limits imposed by dehydration, carbohydrate depletion is a pebble standing in the shadow of the Great Wall of China.

Although most runners drink during long races , the effects of this supplementary fluid intake are limited. The core temperature of the body slowly rises, electrolytes are lost, decreasing the ability of the muscle to contract and the nerves to transmit. Taking in a salt solution certainly helps, but not totally.

If you have been taking long runs (20 miles-plus), you may have achieved a certain amount of adaptation to the problems of heat stress and electrolyte imbalance. That may be the reason you are passing so many other runners toward the end.

As the race goes on, running efficiency slowly declines, and heart rate, respiration rate and cardiac output must increase to meet the oxygen demands of the mitochondria, which must now produce more ATPs than they did before to maintain the same pace.

The process begins like a giant snowball, at first a tiny wad, barely moving, gradually becoming an accelerating enormous mass of snow. Soon the oxygen transport systems and the energy factories of the cell must give way. Oxygen is getting harder to supply as fatigue (prompted by dehydration, electrolyte imbalance, ketone buildup and body temperature increase) sets in. The fatty acids now being used in larger quantities demand still more oxygen. Your cardio-respiratory capacity is reaching its upper limits. You begin to fade.

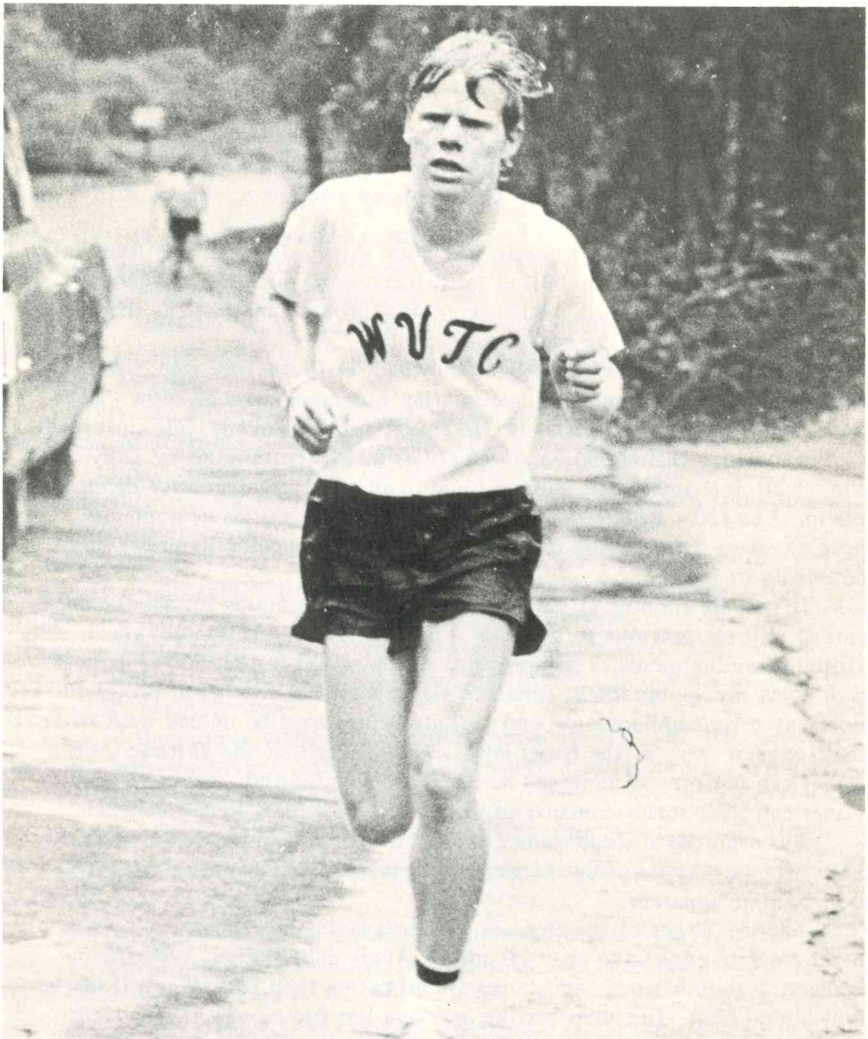
If you are running at sea level and have been training for an extended time at altitude previous to this race, you may have a few minutes grace. Altitude training increases hemoglobin concentration in the blood. It nearly doubles myoglobin levels, enhances the capacity of the heart, produces more extensive capillarization and permits hemoglobin to unload even more of its oxygen cargo at the tissue level. This means that the altitude-trained runner can perform at increased levels of oxygen demand. And also the runner can sustain this concurrently increased pace for a longer distance.

But even the altitude-trained runner is not beyond the reach of fatigue. He may have an edge in oxygen supply capacity, but his frailty will soon become apparent.

The last stages of the race are the most trying (the "halfway" point in the marathon is said to be at 20 miles). Acute dehydration, hyperthermia, electrolyte imbalance and ketosis are all taking their toll. The pH of the body fluids drop. Enzymes become less and less functional. Nerve transmission is sluggish. Efficiency falls off further. Cramping may occur. Ketones may trigger a shallow depression.

Months of training have resulted in the runner being able to come a long way. Perhaps it is his first marathon. Perhaps it is just a faster time over a shorter distance. Nevertheless, the man has met his match. And, as always, his greatest adversary looms from within. Perhaps next time more miles of training will prompt increased adaptations and the limits can be rolled back again for another small victory.

APPENDIX



"The spectrum of fitness if vast. At one extreme we have the distance runners with (oxygen intake) values of 80 milliliters per kilogram per minute." (George Beinhorn photo)

MEASURING FITNESS

Measurement of maximum oxygen consumption rate provides the runner, the coach and the physiologist with a valuable bit of data on the capacity of the runner to perform endurance work. It is indicative of the fitness of all of the body's oxygen dependent systems.

To measure oxygen intake, the runner is required to perform maximal work on a treadmill, bicycle ergometer, or some such device or method which can require varying amounts of work. The air breathed by the runner is collected and measured for oxygen content. These collections are made at intervals. When the subject is working at his maximum, a corresponding sample of air will reveal how much of the oxygen available to him he was *consuming.* This amount of oxygen, measured either in liters per minute or corrected for body weight as milliliters per kilogram of body weight per minute, is his maximum oxygen consumption rate.

The importance of this measurement to the runner is well discussed earlier. It is a bit of information that is valuable to any runner. Unfortunately, not everyone has available to him the facilities to find out maximum oxygen consumption rate. For this reason, several methods have been developed by which any individual can test his or her aerobic capacity and from this estimate oxygen intake. Of course these methods do not have the accuracy or reliability of laboratory measurements. However, they do provide an interesting source of "feedback" for the runner who would like to keep tabs on his state of cardio-respiratory fitness.

The most popular of these methods is the 12-minute run, or its sister the 1.5-mile run, developed by Kenneth Cooper of Aerobics fame. His book *The New Aerobics* provides detailed instructions, and I refer you to it for directions. There is one drawback to the Cooper test, and that is training effects outside of aerobic capacity developments. This is particularly a problem for runners. The training of the muscles and the nerves of the legs to run is partly independent of any improvements in aerobic capacity. Thus, when you take the test several times (especially during a regular running program), the results may make you look better than you really are. For this reason, it is wise to choose a "stress" (as provided by running 12 minutes, etc.) to your aerobic capacity which does not involve movements which you are regularly training your body to perform.

A modification of the Harvard Step Test satisfies this requirement (unless you are an active soap-box orator). If you are male, select a platform which is 40 centimeters (15") high, or if you are a female, select a platform 33 cm. (13") high. After taking your weight, locate this platform where a clock with a second hand can plainly be seen. The test involves stepping onto (first one foot then the other) and off the platform at a rate of 30 times per minute. Make sure you step completely up on the platform before stepping down.

At the end of five minutes (or as long as you can go if you can't make five minutes), take your pulse *immediately*. It is preferable to take it during the last minute of exercise if possible, but this takes some practice.

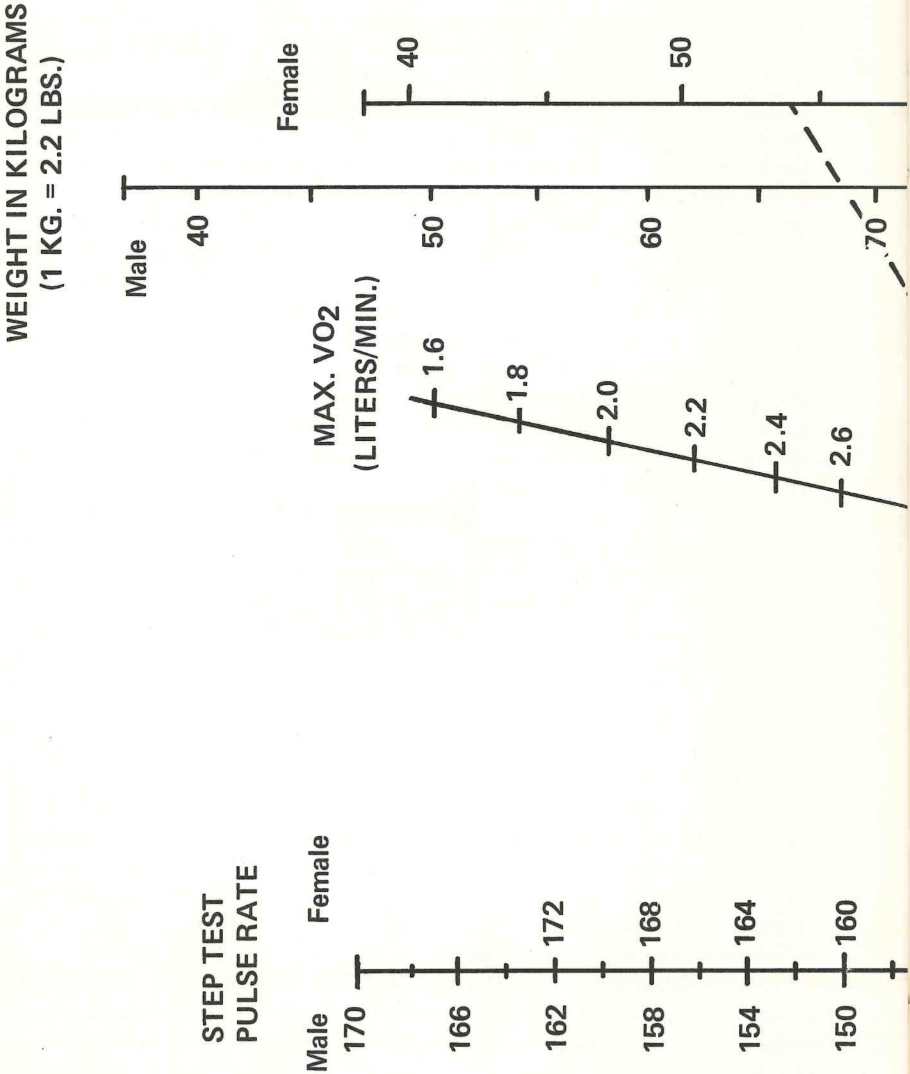
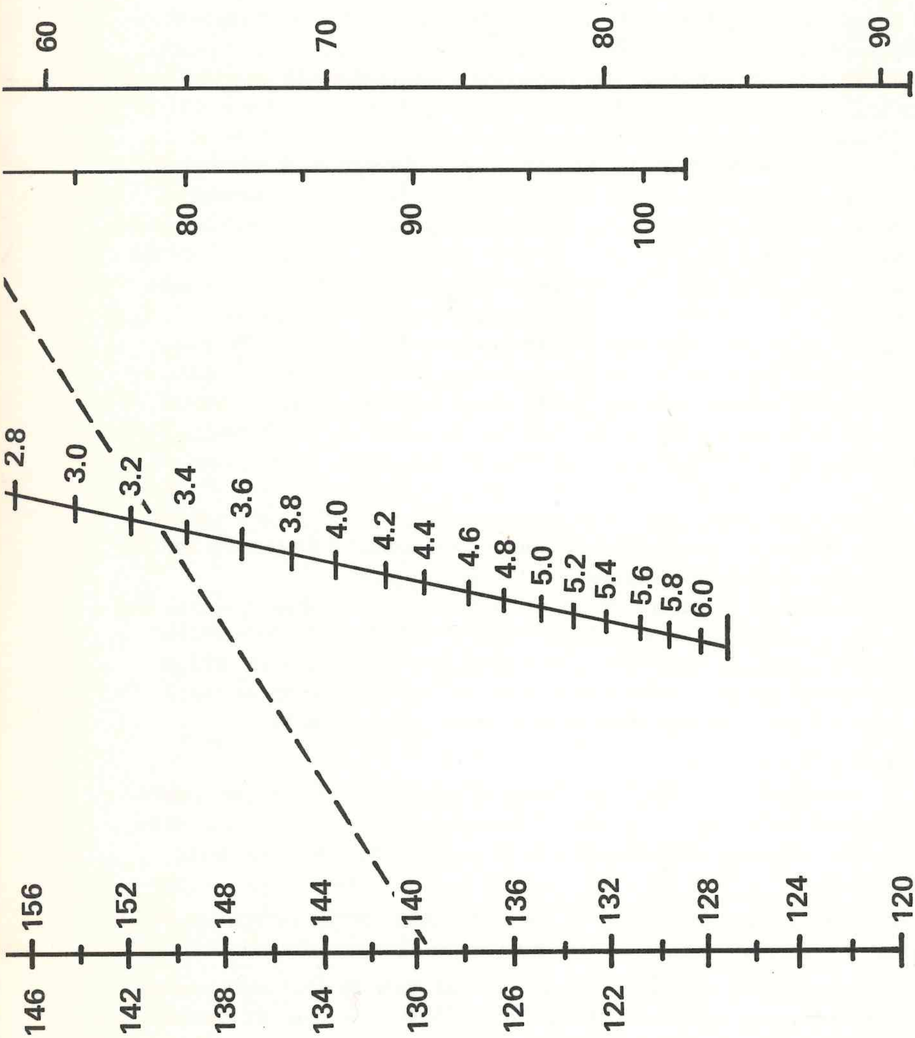


FIGURE SEVEN A Nomogram for Estimating Maximal Oxygen Uptake (Astrand, 1970).



Sample (dashed line) is for a male weighing 54 kg., who achieved a pulse of 129 during step test. Maximal oxygen uptake is 3.3 liters, or 61.1 ml./kg./min.

Count it for 15 seconds and multiply times four. This test is a lot more strenuous than it sounds. So if you are not exercising regularly then it should be taken only under medical supervision.

Once you have your pulse and your weight in kilograms (divide your weight in pounds by 2.2 to find your weight in kilograms), you can use figure seven to estimate maximum oxygen consumption rate simply by drawing ing a straight line between your weight on the right (watch what sex you classify yourself as) and your measured pulse rate on the left. The point at which this weight line intersects the oxygen intake line will give you your maximum consumption rate in liters per minute. To convert this to the more common milliliters per kilograms per minute figure, simply move the liters/min. figure three places to the right (e.g., 3.4 becomes 3400) and divide your by weight in kilograms. A sample test is shown in the nomogram.

Since you're in the mood for finding out what's going on in your body, perhaps you'd like a crude estimate of your percentage of body fat (i.e., the amount of your total body weight which is fat). The amount of fat you're carrying around has a lot to do with performance. (Notice you divided *by* your weight to find maximum oxygen intake. Experiment with a lower body weight figure in this calculation and see what happens.) If they're runners, even 98-pound weaklings worry about being overweight. Weight in the form of excess fat has certain obvious drawbacks to the runner. Percentage body fat is the best way to determine whether or not you have an excess.

The average young man (not considered fat by most) usually carries about 20% body fat. Good distance runners are usually between 6% and 9% body fat. For serious club runners, 9-11% seems optimal.

Again there is no substitute for accurate laboratory measurements. But to give you a rough idea of your percentage of body fat, I've constructed the enclosed scale (see Figure 9). This method *at best* is accurate within 2%. The more you deviate from the norm (i.e., the more portly or the more lean you are), the less accurate your measurement will be.

How to use the scale:

1. Determine your reciprocal ponderal index by dividing your height in inces (barefoot) by the cube root of your weight as measured in pounds (nude). The following table should help in finding your ponderal index (see Figure 8).

2. Simply find your R.R.I. on the scale and note the percentage body fat which corresponds with it on the right.

This calculation will allow you a rough estimate of your body composition. With this information, and the data gleaned from your oxygen intake, you are two steps in the direction of increasing your body awareness.

FIGURE EIGHT Ponderal Index Calculations

	HEIGHT																		
WEIGHT	5'0"	5'1"	5'2"	5'3"	5'4"	5'5"	5'6"	5'7"	5'8"	5'9"	5'10"	5'11"	6'0"	6'1"	6'2"	6'3"	6'4"	6'5"	6'6"
100	12.9	13.1	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0								
105	12.7	12.9	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0							
110	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.1						
115	12.4	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0					
120	12.2	12.4	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0				
125	12.0	12.2	12.4	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0			
130	11.8	12.0	12.2	12.4	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0		
135	11.7	11.9	12.1	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.6	13.8	14.0	14.2	14.4	14.6	14.8	15.0	
140	11.6	11.8	12.0	12.1	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.7	13.9	14.1	14.3	14.5	14.6	14.8	15.0
145	11.4	11.6	11.8	12.0	12.2	12.4	12.6	12.8	13.0	13.1	13.3	13.5	13.7	13.9	14.1	14.3	14.5	14.7	14.9
150	11.3	11.5	11.7	11.9	12.1	12.2	12.4	12.6	12.8	13.0	13.2	13.4	13.6	13.7	13.9	14.1	14.3	14.5	14.7
155	11.2	11.4	11.6	11.7	11.9	12.1	12.3	12.5	12.6	12.8	13.0	13.2	13.4	13.6	13.8	14.0	14.1	14.3	14.5
160	11.1	11.3	11.5	11.6	11.8	12.0	12.2	12.4	12.5	12.7	12.9	13.1	13.3	13.5	13.7	13.8	14.0	14.2	14.4
165		11.1	11.3	11.4	11.6	11.8	12.0	12.2	12.4	12.6	12.8	13.0	13.1	13.3	13.5	13.7	13.9	14.1	14.3
170		11.0	11.1	11.3	11.5	11.7	11.9	12.1	12.3	12.5	12.6	12.8	13.0	13.2	13.4	13.5	13.7	13.9	14.1
175			11.0	11.2	11.4	11.6	11.8	12.0	12.2	12.4	12.5	12.7	12.9	13.1	13.3	13.4	13.6	13.8	14.0
180				11.1	11.3	11.5	11.7	11.9	12.1	12.3	12.4	12.6	12.8	13.0	13.2	13.3	13.5	13.7	13.9
185				11.0	11.2	11.4	11.6	11.8	12.0	12.2	12.3	12.5	12.7	12.9	13.1	13.2	13.4	13.6	13.8
190					11.1	11.3	11.5	11.7	11.9	12.1	12.2	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.7
195					11.0	11.2	11.4	11.6	11.8	12.0	12.1	12.2	12.4	12.6	12.8	13.0	13.2	13.4	13.6
200						11.1	11.3	11.5	11.7	11.9	12.0	12.1	12.3	12.5	12.7	12.9	13.1	13.3	13.5

*Ponderal Index = height in inches divided by cube root of weight in pounds.

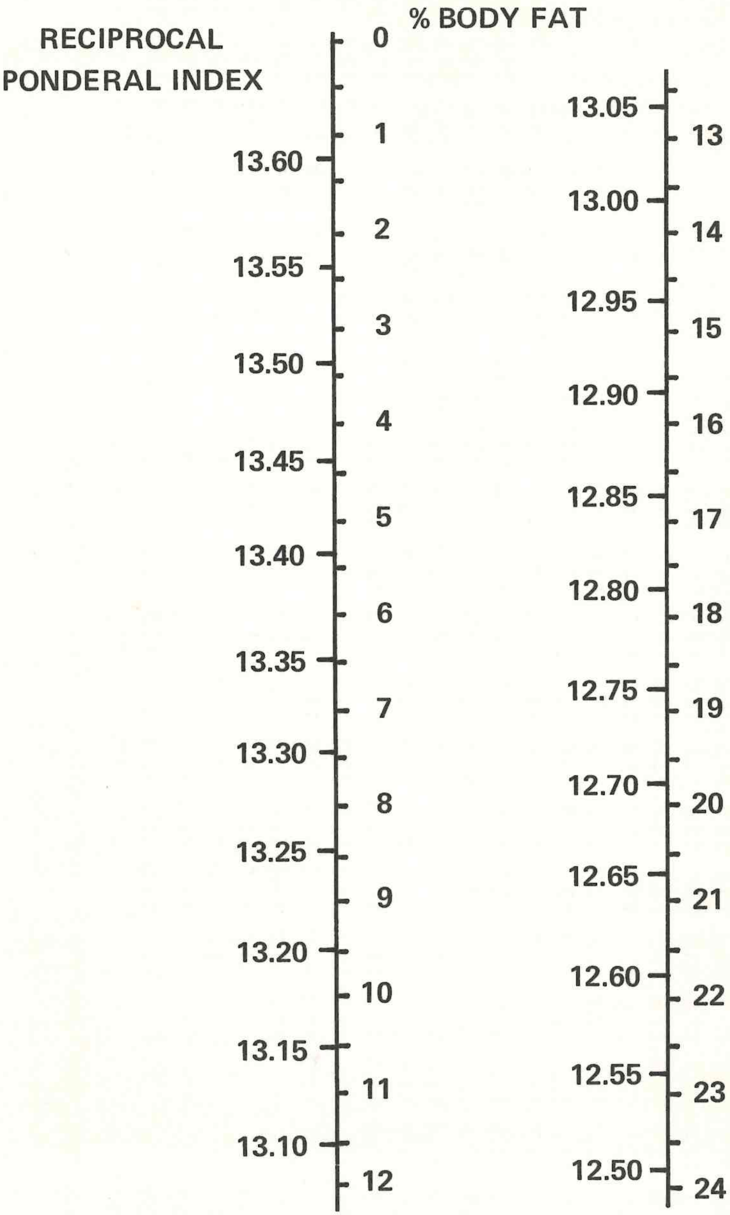


FIGURE NINE Nomogram for Determining Body Composition

"The greatest reward of knowledge is not that it can aid us in achieving our goals, but that it can add dimension and enjoyment of what we do. Thus the experience of running can be so much richer if we understand the subtle physiologic changes we undergo in training and during a race." (Bill Herriot)

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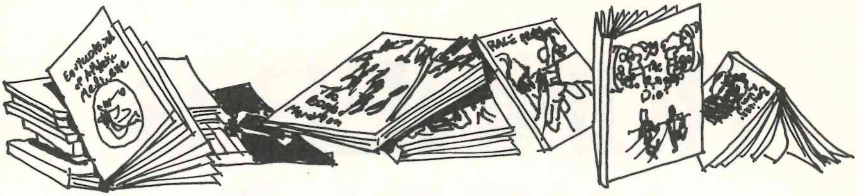

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THE RUNNING BODY

". . . What happens, physiologically, during a year of training to allow a former arm-chair athlete who couldn't wheeze through a mile in 10 minutes to string together 26 sub-seven-minute miles for a three-hour marathon? What causes cramping? How does carbohydrate-loading work? What is fatigue? How does altitude training enhance performance? To understand the vast array of physiological adjustments . . . is to experience running more fully. It is toward this end that this booklet is written."

COVER PHOTO:
The running body gets no sterner test than in uphill cross-country racing. (John Cooper)

LEFT:
Top woman distance runner Eileen Claugus. (M. Julius Baum photo)