THE ENERGY COST OF AMBULATION FOR TRAUMATIC PARAPLEGICS

by

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I wish to acknowledge helpful counsel and technical instruction from Robert Bolasney, Technician, Pulmonary Laboratory, Veteran's Administration Hospital, Denver, Colorado.

also from the members of my thesis committee who were most generous in the guidance of this project.
The Energy Cost of Ambulation for Traumatic Paraplegics

Thesis directed by Professor Jerome Gersten

The purpose of this study was to determine the energy cost of ambulation in traumatic paraplegics, and to lay the groundwork for continued study into the metabolism of these patients under various conditions. Objects of consideration were the level of lesion and the rate and type of gait.

Samples of air were collected with the Max Planck respirometer, and gas analysis was done by the Scholander method. The patient walked for six minutes, and recovery samples were taken to determine oxygen debt. Calculations were made on the basis of calories consumed per kilogram of body weight per minute, and also calories per meter walked per kilogram of body weight. Comparison of these patients with normal subjects showed heavy energy expenditure on the part of all paraplegics, with marked increase as the level of lesion ascends. The question is raised as to the need of ambulation in all cases, and the substitution of one hour of standing daily is suggested as ample for physiologic benefit in those patients in whom ambulation is done at excessive cost.

Consideration of all aspects of paraplegia is encouraged, with ambulation as a less important goal than other goals, and caution advised in urging too much physical activity on someone who already is suffering from severe stress reaction, and with limited respiratory ability. This information is also useful in showing certain patients that ambulation is an attainable and useful goal.
This abstract of about 235 words is approved as to form and content. I recommend its publication.

Signed

Jerome Gersten, M. D.
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INTRODUCTION

Our purpose in conducting this study is to determine the energy cost to the traumatic paraplegic in ambulating, to determine whether level of spinal cord damage can be related to the energy cost, and to determine whether methods of training can be improved by the information obtained from this study. This latter objective might be reached by determining the efficiency of various types and speeds of gait, which are most efficient for each patient, as well as the effect of various types of bracing.

In the rehabilitation of a paraplegic patient a great deal of time and training is expended by a fairly large staff in order to get this patient to the point of independent ambulation. There is good reason to re-evaluate the technic of rehabilitation and see if ambulation is a wise goal in all cases, and if, in some cases at least, it would be possible to determine by the level of injury, or by energy studies in the preliminary phases, that ambulation would not be a fruitful goal, and that the time and money would be best used in some form of vocational training instead. Ambulation is stressed in much of the literature as the great objective in rehabilitation, and in the eyes of the public much concern is placed on whether or not the patient will walk again, yet there might be more useful goals than this, and it is our purpose to determine whether some plan could be devised whereby the feasibility of ambulation could be determined in each case, without going to the time consuming and expensive method of the training
Paraplegia refers to that disability in which there is paralysis of the lower extremities with or without involvement of the upper extremities. While there are various causes for such a condition, this study will refer to traumatic paraplegics only, and as closely as we can judge, to patients with complete cord transection to avoid bringing in too many variable factors, such as functional muscle below the described level of injury, etc. From here on, then, the word "paraplegia" will refer only to traumatic cases, unless otherwise defined.

Because there are some 100,000 paraplegics (traumatic and others) in the United States (1), with the number increasing steadily due to automobile accidents and other forms of trauma, this is a problem of real concern to the medical profession and to the community as a whole. Their care is a long term problem, involving many personnel of special talents and also incurring considerable expense. Any research which will improve the level of medical care, or reduce the expense and time while providing equally good care, should be of value to the technic of rehabilitation. In this day, with the modern technics of surgery and the use of antibiotics and other refinements which have been added to the care of these cases, more of these patients are surviving the acute injury than ever before, and with a better understanding of rehabilitation technics these patients have an increased life span, and they form a sizeable problem to the medical and social community.

A preliminary survey of four traumatic paraplegics, five polio and two cerebral palsy paraplegics was made in 1956 by Gordon (2, 3) and he stated that an attempt would be made to relate energy consump-
tion to level of lesion as the study progressed, but he did not continue the study.

We felt that the process of rehabilitation needed the information provided by such a study in order to help provide realistic goals for the patient, and to direct the energies and financial expenditure of the rehabilitation team into the most practical channels.

While there are physiological benefits to be derived from ambulation, as well as the physical independence gained by getting from one place to another, we felt that the ambulation must serve a useful purpose to justify the training program, and it must not be done in a way that could cause damage to the patient in terms of too great a physiological cost. Paraplegics who were interviewed admitted that they needed the stretching and exercise that accompanied standing, and they had been educated to believe the physiological benefits to calcium metabolism, the prevention of contractures and other benefits described in medical literature, but many of those who had two or three years of experience were not enthusiastic about the benefits of ambulation as a means of progression. They preferred their wheelchairs, and stated that ambulation was very hard work and made them very tired, and implied that the benefits did not justify the cost in energy. It has been the experience of people working with paraplegics that a fairly high percentage of them revert to wheelchairs as soon as the training and persuasion of frequent visits to the training center are discontinued and they are put on their own (4). If this study would help to establish a "yardstick", such as level of injury, whereby the rehabilitation team could maintain a better ratio of patients who would continue to ambulate when released from the intensive training program,
it would be a useful project in furthering the goals of rehabilitation training.

In brief, then, our problem was to determine the energy cost of ambulation in paraplegics, and search for means of making ambulation easier, and for methods whereby a decision could be made early in the rehabilitation phase as to the feasibility of making ambulation a goal in each particular case.

no one method has yet achieved universal acceptance. We will here outline some of the methods of measuring energy metabolism and discuss them in order.

- Lactic acid determination
- Measurement of total expired volume
- Measurement of body temperature
- Creatinine blood level
- Pulse rate
- Oxygen consumption

Lactic Acid Determination

During muscular activity lactic acid is produced from glycogen, and in the recovery from exercise part of it is resynthesized to glycogen. The rest is metabolized to oxygen and carbon dioxide. In 1922 Hill, Long and Lupton (5) first attempted to estimate energy cost from the lactate produced, and since then others have attempted to do this, among them Jarrell (6) in 1928.

Wells, Balke and Van Pappen (7) checked pulse rate, blood pressure, oxygen consumption, pulmonary ventilation and lactic acid.
HISTORICAL DEVELOPMENT OF VARIOUS METHODS OF STUDY OF
ENERGY METABOLISM

In the study of energy metabolism it becomes evident that workers in this field are searching for newer and easier methods and that no one method has yet achieved universal acceptance. We will here outline some of the methods of measuring energy metabolism and discuss them in order.

Lactic acid determination

Measurement of total expired volume

Measurement of body temperature

Creatinine blood level

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Lactic Acid Determination

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during various intensities of work. Their graph shows a good relationship between ventilation, lactic acid, and oxygen consumption, but it cannot be considered close enough so that one could determine oxygen consumption from the lactic acid curve.

Huckabee (8) states that lactic acid accumulation can be produced by hyperventilation as well as by exercise, and "... changes in blood lactate in exercise are not correlated with oxygen debt, and may err in either direction."

He mentions that there may be two lactic acids, one of which is more closely related to oxygen debt than the sum of both. This is called "excess" lactic acid, and is determined by the relationship to pyruvate blood levels.

Since the metabolism of lactic acid takes place in the liver, the lactic acid figures would have more accuracy in normal people than in paraplegics, who often have amyloidosis of the liver, and might conceivably give still more inaccurate figures than in normal subjects. For these reasons we did not use this method, as we felt it would add no necessary information to this study.

Measurement of Total Expired Volume

It is well known to all who work in the field of energy studies that conventional methods require many analyses of expired air, and it would be desirable to reduce the amount of work required to permit more wide use of energy studies. Durmin and Edwards (9) are critical of those who advocate analysis of carbon dioxide alone as an index of energy cost, but favor further study of the use of total volume expired as an index.
They state that analysis of carbon dioxide output alone has been justly criticized by such authors as Hill and Campbell (1921) (10), Orr and Kinlock (1921) (11) and Gairns and O'Brien (1922) (12). The reason for criticism of this method is that at the beginning of exercise the amount of carbon dioxide in expired air may alter to quite a large extent during the first ten or twenty minutes, and may vary from minute to minute. Thus any short term collection, even during the so-called "steady state" involves considerable error.

These authors refer to other workers in the field of respiratory physiology who have noticed the approximately linear relationship between pulmonary ventilation and oxygen consumption. Boothby (13), Bock et al. (14), Taylor (15), Grodins (16) and Abbot and Bigland (17) among many others, have noted this relationship.

During light and moderate exercise, when pulmonary ventilation is normally less than 50 L/min (BTPS), the oxygen consumption of any one individual is directly proportional to his pulmonary ventilation. With harder exercise, the ventilation on the average increases disproportionately to the consumption of oxygen, and the relationship between the total ventilation and the oxygen consumption becomes a parabola instead of a straight line (16). However, the range where the relationship is linear covers the majority of everyday activities.

In checking the practicability of this method of estimating calorie expenditure, an analysis was made of the results of two field tests by Passmore et al. in 1952 (18) and 1955 (19). These tests showed a fairly large individual variation and a common line for all subjects could result in considerable error when applied to an individual.
However, by using six points, at various levels of work, a regression line can be obtained that will give a sufficiently accurate measure of the relationship between pulmonary ventilation and energy expenditure. These workers also found that the relationship between pulmonary ventilation and energy expenditure does not remain linear at levels below 15 L/min consumption. In other words, this method was most accurate between 15 and 45 L/min ventilation.

Their conclusions were that this method could be used to determine energy expenditure at any level of work by measuring pulmonary ventilation alone, if six points are determined by gas analysis, and a line of regression drawn. Since this involves six gas determinations, it would mean just as much work, with less accuracy than conventional methods, and for this reason we did not use this method, although it may be useful for long term studies such as a day of work.

Another method for measuring total volume is by way of the Venturi tube as described by Warring and Siensen (20). The Venturi tube has been used by engineers for many years for making measurement of dry gases, and does so with accuracy. In brief, the Warring method consists of filling a bag with a measured quantity of oxygen (300 cc or more) and attaching it to the small side arm of the Venturi tube. After the time of expiration is over, the remaining oxygen in the bag is measured by a well oiled glass syringe.

We believe that with a Venturi tube of known inside diameter and a side arm of known internal diameter, accurate measurement of total flow is possible by measuring the volume flow through the side arm. The method used here, measuring from a rubber bag with an oiled syringe was difficult for us to accept, inasmuch as the end point did not seem easy
to determine. Since 101 cc removed from the bag indicated 32.3 L of total volume, an error of only 10 cc would be compounded to an error of over 3 liters, which would be a significant amount. This method might have merit in experienced hands, but we did not feel that we should use it until we had more familiarity with its possibilities. Also this method does not allow for sampling the expired air, and introduced the additional question of accuracy when predicting energy cost by total volume expired, which we have already discussed.

**Measurement of Body Temperature**

Holtze (21) states "...body temperature rises to a definite and constant level, the height of which is determined by the intensity of work*. He states that this is true regardless of room temperature, the presence or absence of fans, and humidity of the air. He also says "...the rise of body temperature was practically proportional to the oxygen intake".

This information serves a useful purpose inasmuch as a person who had an elevated temperature could not be considered abnormal if he had been exercising. The author also uses this information to encourage "warming-up" before doing strenuous exercise, especially in the strenuous short term sports.

Inasmuch as our patients could only ambulate for a short time, in many cases less than ten minutes, we could not use this method, since the authors stated that the body temperature did not become stable until 30 to 50 minutes of exercise had been performed at a steady rate. However, we felt that this information was of interest in the field of energy studies, particularly long term work. It must
be remembered that paraplegics have disturbances of the sympathetic system and do not respond like normal people, and would not give usable figures in such a study (see under Metabolism, page 24).

Creatinine Blood Levels

Standard, Wills and Waterlow (22) in discussing indirect indicators of muscle mass in malnourished infants state "It has long been supposed that creatinine output is a measure of muscle mass". Recently Miller and Blyth (23) have shown in a group of adults that there is a good correlation between 24-hour creatinine excretion, basal oxygen consumption and lean body mass.

Since paraplegics have a considerable muscle mass which is unable to function, it was of interest to us to find out if this method could be used to determine functioning muscle mass, as opposed to non-functioning muscle. We felt that standard basal metabolism figures should not apply to paraplegics, inasmuch as they were computed on body weight, and in normal people a large portion of this body weight is functioning muscle. But in paraplegics, body weight is not a true index of functioning muscle, and only a relatively small amount of muscle is used to ambulate in some of these patients. If creatinine, or some other substance, would be an index of functioning muscle mass, it would help establish how much muscle was carrying the work load, and be a help in energy study research.

Pollock et al. (24) did creatinine studies on 18 paraplegics, who were disabled either as a result of trauma or poliomyelitis, and compared these results to those obtained in hemiplegics and some amputees. Patients with paraplegia and severe nerve root injury, or
plexus injury showed high creatinine output, and low blood creatinine. Patients with paraplegia without nerve root or plexus injury, hemiplegics, or poliomyelitis patients did not show these changes. In amputees creatinuria was seen, suggesting that it occurs when muscle mass is less than normal, but Pollock refers to Milhorat and Wolff (25) who suggested that it was due to improperly functioning muscle, and in careful debridement of such muscle no creatinuria occurred later. Since creatinuria is not found in hemiplegia, or spinal injuries uncomplicated by nerve root damage, it is not yet established just what it does mean, and further work needs to be done before it can be helpful in this study. Kent (26) reports two patients with cervical spine lesions, in whom blood creatinine levels were normal.

Pulse Rate

This observation is discussed by Asmussen and Molbech (27) who also discuss the laborious and, to the patient, uncomfortable methods being used to do energy studies, and they refer to the work of other authors in finding easier methods. They state that several authors have, therefore, developed methods by means of which the maximum oxygen uptake can be estimated from determinations of other parameters made during submaximal work (28), (29), (30). These methods are based on the observations that, up to a certain limit, the pulse rate during muscular work is rectilinearly correlated to oxygen uptake. This upper rate of heart beat was found by Robinson (31) and by Astrand (32) to decrease with age from about 195 beats/min at 20 years of age to about 160 beats/min at 65 years of age. Asmussen
and Hemmingsen (30) utilized these data in presenting a curve and a formula by means of which the maximum oxygen uptake can be estimated from values obtained during submaximal work on the treadmill or while pedalling a tricycle with the arms, on a treadmill. Their procedure formed the basis for the work described by the authors (27).

The method involves doing air collection and analysis during submaximal work, a method which does not actually save any time in short term studies, and since there is no substitute for ambulation in a paraplegic beyond actually doing the work, we felt that this method was not of value to us, but was worth recording in the over-all survey of methods.

Oxygen Consumption

Since this method has a long historical background, we think it well to develop this aspect first.

Historical

In the development of experimental methods for determining the energy expenditure of man, one of the first concerned the increased utilization of oxygen in muscular work. This is well narrated by C. G. Douglas, (33), inventor of the famed Douglas bag, and by George Rosen, in a textbook edited by McBrooks (34). Between 1775 and 1785 Lavoisier showed the true nature of oxidation and demonstrated that in respiration oxygen was used up and carbon dioxide was produced, and that these changes were greater in quantity during muscular movement, thus giving the conclusion that the heat of the body was essentially a slow combustion involving the oxidation of carbon to carbon dioxide.
and water, and giving a clue to the means by which an estimate might be made of the varying output of the living animal. And so Lavoisier made it clear that an index of energy expenditure could be either the amount of oxygen consumed, or the rate of loss of heat from the body. About 1838 Justus von Liebig created a unified concept of metabolic activity by classifying the nourishment of animals and men into three fundamental categories: protein, carbohydrate and fat, and showed how protein was used to build up or repair the organism while the last two were used for fuel. He determined how much oxygen was needed to burn the different classes of food and how much energy was released as measured by heat.

Early in the 19th century, the Academy of Sciences in Paris offered a prize for the best thesis on the origin of animal heat, and it was awarded in 1823 to a young scientist named Despretz. He carried out experiments involving animal calorimetry, but the results were inconclusive. The amount of heat produced by the animal and that to be expected from its ingested food was so marked that he assumed that in the organism the chemical behavior of the elements was subject to the influence of the vital force.

More significant were the experiments reported by Baussingault in 1839. He established the first balance between the carbon, hydrogen, oxygen and nitrogen in the ingested food and in the excreta of animals, and compared actual carbon dioxide production with that which had been calculated.

In 1849 Regnault and Reiset measured the respiratory quotient of different animals and endeavored to show how it was influenced by
different foods. Their equipment involved placing the animal in an air-
tight bell jar which was immersed in a water bath. The carbon dioxide
in the air was removed by a potassium hydroxide solution in a pump,
which constantly removed air from the chamber and returned it, the
bicarbonate which was formed being estimated subsequently. Oxygen was
supplied in a quantity sufficient to maintain the pressure within the
bell jar. This apparatus was thus a closed system and was a prototype
on which much subsequent apparatus was based. Krogh (1906) actually
carried out the experiments which could be considered as convincing in
the use of this type of apparatus.

Edward Smith (1859) designed the first portable open-circuit
apparatus for experiments on man, an apparatus which was essentially a
valved facepiece and a dry-gas meter and used ordinary air. Douglas
states that he repeated the same experiments with the bag method on
himself and came up with the same figures for CO₂ production which
Smith arrived at on himself half a century earlier.

In 1861, Carl Ludwig offered a critical discussion of the prob-
lem of animal calorimetry and explained why one was justified in expect-
ing that the heat produced by animals would equal that to be derived
from their nutriment. He pointed out possible sources of error in such
studies, and indicated how they could be made more precise.

Pettenkofer (1862) was of the opinion that a mask or mouthpiece
and respiratory valves might interfere with natural breathing, and he
felt that some toxic volatile substance might be given off in expired
air and accumulate to the harm of the subject. He designed a respira-
tion chamber of 450 cubic feet capacity, which was paid for by King
Maximilian II of Bavaria. This chamber was ventilated by drawing fresh air through it by a pump. Its volume could be varied between 15 and 75 cubic meters per hour and was measured by a gas meter. A sample of the air leaving the chamber was passed through sulfuric acid to remove water vapor, barium hydroxide absorption tubes removed carbon dioxide and a small gas meter measured the actual volume. Thus he was able to obtain the carbon dioxide production. Voit (1875) used a similarly designed apparatus.

Hoppe-Seyler (1894) designed a respiration chamber for man on the same principle as that used by Regnault and Reiset, employing the same type of potassium hydroxide pump. This chamber was 170 cubic feet in capacity and he was able to determine both oxygen and carbon dioxide values. About this same time others built large human respiration chambers in Stockholm and Helsinki, and in the latter city energy studies were made on persons of different occupations.

At the beginning of the century, Zuntz built a respiration chamber of 2,800 cubic feet capacity to study the carbon dioxide output and oxygen intake of large domestic animals. Jacquet (1905) used an open-circuit method in which air was drawn by a pump through a chamber of 50 cubic feet capacity, in which the subject could lie or sit, and samples of air leaving the chamber were taken and analyzed. Lavoisier had measured the heat output of animals by means of an ice calorimeter, but it was not until D'Arsonval (1886) described his differential calorimeter that a satisfactory method for animal calorimetry became available. In 1905 Atwater and Benedict built a respiration calorimeter in which the calorimetric chamber also served as a closed circuit respiration chamber on the Regnault-Reiset principle.
All of the apparatus described so far, and also many of those built since then, are suitable for experiments of long duration, but information about human energy output need not always be long \( (33) \), and satisfactory information can be obtained from short duration experiments. Geppert and Zuntz in 1887 introduced an open-circuit apparatus in which the subject breathed through a mouthpiece and respiration valves, the expired air being directed through a wet-gas meter. As the drum of this gas meter rotated, a gearing on its shaft lowered the outlet tube of a gas burette which had been filled at the beginning with liquid; the burette was therefore gradually filled with a proportional fraction from each successive respiration; and analysis of this composite sample and the total volume recorded by the meter allowed the respiratory exchange to be calculated. The original form of this apparatus was only suitable for the laboratory, but by replacing the wet-gas meter with a dry-gas meter, the apparatus could be carried on the back, and this apparatus was used during rest and exercise by Suntz, Loewy, Mueller and Caspari \( (1906) \) and by Durig, Kolmer, Rainer, Reichel and Caspari \( (1909) \).

In 1940 Kofranyi and Michaelis made some modifications on this apparatus and it has been used since for field observations. This is the type of apparatus used during our own survey, as we shall describe later. There have been other short period machines built, one described by Benedict \( (1912) \) and used extensively in the Nutrition Institute of the Carnegie Institution of Washington. This apparatus is essentially a pipe circuit around which air is driven by a blower, the subject breathing back and forth into this circuit while water vapor and carbon dioxide are absorbed and oxygen compensated on the Regnault-Reiset
In 1911 Douglas introduced the bag method, and this has been very useful for short period work, as have the various spirometer units which have been introduced, such as used by Speck (1892) and Tissot (1904) which were very bulky. Since these methods have been used and accepted widely, this work justifies the indirect method for estimating the energy output. The calorimeter has been largely abandoned in favor of the indirect method, and this has been made more workable by better apparatus, and newer methods of gas analysis.

Carbon dioxide has the property of a high absorption coefficient in the infra-red region (34), a property which is common to methane and nitrous oxide, but which is not found in oxygen or nitrogen. Instruments for analysis of carbon dioxide can be designed so as to be specific for this one gas alone. In brief, the unknown gas is heated by infra-red, along with a known pure sample of carbon dioxide and the pressure difference between the two gases is recorded as voltage by a suitable device, and readings taken are as accurate as 1 percent. The apparatus commonly used is the Liston Becker apparatus.

In oxygen analysis, by methods which give continuous readings, the apparatus depends upon the special property of oxygen, almost unknown in other gases, of paramagnetic susceptibility. If a strong magnetic field is produced around the junction of a small side tube with a main channel through which gas is flowing, oxygen will be attracted into the small side tube. The flow rate at a given magnet field strength is proportional to the oxygen content, and this can be measured with an accuracy of 1 percent. The apparatus commonly used for oxygen analysis by this method is the Pauling apparatus.
These machines cannot measure air in an expiration air stream, since the percentage of oxygen and carbon dioxide are constantly varying, and the needles will fluctuate back and forth with no meaning, but they can be used in a well mixed sample at some point beyond the immediate expiration stream, keeping in mind that thorough mixing can itself be a sizeable problem. Both of these machines are very "temperamental" and require frequent calibration to maintain accuracy, so we did not use them in this survey.

Indirect calorimetry is subject to error, and these experiments must be done as carefully as possible in order to eliminate all possible sources of error, but there is no other method yet known and accepted that can compare with indirect calorimetry (35), particularly in short term work. For this reason we chose to use oxygen consumption as the index of work in our patients, in preference to the other methods discussed previously, inasmuch as this was the only reasonably accurate method which could be used in short term work, such as walking by a paraplegic, who, in most cases, could walk for only a short period of time.

The Douglas bag method has been widely accepted as the standard technic for collecting air samples, the bags coming in various sizes so that as much as 200 liters of air could be collected in one bag. Since the usual method is to collect two minutes of resting air, then three 2-minute samples of air during work, and three 4-minute samples during recovery, this would involve the use of seven bags. This large number of bags would involve no serious problem under the usual conditions where the apparatus is stationary, but in studying paraplegics we had
to have a mobile apparatus, which could travel along with the patient and a therapist, and not impede the walk. Seven large bags, when partially filled with air, would present a problem of maneuverability, which seemed cumbersome, so in spite of the well earned reputation of this method, we chose to find something more portable, so as not to involve the patient in a fall.

Physiology of Oxygen Consumption

Houssay (36) states that the commonly known results of exercise, such as "shortness of breath", increased respiratory and pulse rate, sweating and rise in body temperature are all signs of an increased metabolism. He states "muscular contraction is accompanied by an increase in oxygen consumption because, when working, the muscles require a supplement of energy, which is obtained by burning a larger amount of foodstuffs. This increase in combustion causes an increase in the oxygen consumption of the whole organism, and several adjustments in the respiratory and circulatory functions must be made to assure the arrival of more oxygen to the active muscles." He also states that the rate of oxygen consumption increases proportionally to the work performed.

According to Karpovich (37), the cell takes no more oxygen than it needs and man has no oxygen supply except what he receives from the inspired air. At rest the body requires 200 to 300 cc of oxygen each minute. In exertion this need is greatly increased, so that the consumption of oxygen by muscle may be as much as fifteenfold that of resting muscle. The muscle weight is 40 percent of the body weight and 1 kg of muscle at rest uses 3 cc of oxygen/min. Therefore, in a
70 kg (154 lb) man, muscle will consume at rest 84 cc/min, leaving 216 cc/min to be consumed by other parts of the body. Assuming that only the heart and skeletal muscles show any sizeable increase in oxygen consumption during exercise, in a man who uses 4,500 cc of oxygen/min in vigorous exercise, if the heart uses 250 cc, the skeletal muscles will use 4,054 cc. However, since all muscles are not working at their full extent, some muscles will actually consume 50 times more oxygen during vigorous exercise than during rest.

Karpovich also states that if exercise is moderate and uniform, the oxygen intake rises gradually and then in a minute or two levels off and remains at this level for the duration of the exercise. This is called the "steady state" in which oxygen intake equals oxygen utilization. The oxygen level depends on the intensity of work, and rises with a rise in intensity of work. The extent of rise of the level of oxygen consumption is limited by the individual's maximum capacity for oxygen intake, being 2 L/min in the untrained persons and as high as 5.35 L in Lash, the holder of the 2 mile 1936 Olympic record.

Taylor (38) states "...the rate of oxygen consumption is a highly significant physiological variable not only because it represents the physiological cost of work but because it gives evidence of the transport capacity of the circulatory and respiratory mechanisms." It is a prevailing view that the ability to absorb oxygen is a limiting factor in individual physical performances, and that oxygen consumption is by no means always deficient at exhaustion levels. Oxygen consumption is an index of the physiological cost of work (5), and a capacity to maintain a high oxygen consumption over a period of time demonstrates...
a large degree of cardiovascular and respiratory fitness.

Guyton (39) states that under normal conditions the quantity of oxygen carried to the tissues by each 100 ml of blood is approximately 5.3 ml combined with hemoglobin and 0.18 ml in the dissolved state, or a total of 5.5 ml for every 100 ml of blood. This is not the total content of oxygen in the blood, but the amount given up to the tissues, the A-V difference. With a cardiac output of approximately 5,000 ml per minute, the calculated normal quantity of oxygen delivered to the tissues per minute is about 275 ml. The intracellular oxygen pressure \( (P_{O_2}) \) is 30 mm Hg, and it falls to 20 or less on exercise, thus increasing the diffusion rate. The pressure \( (P_{O_2}) \) at the arterial end of the capillary is 100 mm Hg while the pressure in the interstitial spaces is 35 mm Hg.

Oxygen Debt

During strenuous exercise, the body does not furnish the muscles with all the oxygen that they require, and the body "goes in debt" for the oxygen it needs and pays off the debt during recovery. The muscle is able to contract because of its ability to work under anaerobic conditions for a short time. After a short period of work, the "steady state" is reached, in which debt is no longer incurred and the average man can maintain the steady state for a long time if the oxygen need is not over 2 L/min (40, 41). Oxygen that is used to return the anaerobic systems back to their normal state is used to turn adenylic acid back to adenosine diphosphate, and some is required to change adenosine diphosphate back to adenosine triphosphate, and to re-form phosphocreatine. Lactic acid is resynthesized to glycogen and oxygen
is returned to the myoglobin oxygen buffer system of the muscles and to
the greatly depleted hemoglobin of the blood. Thus it can be seen how
the oxygen debt can allow the body to operate on borrowed energy dur­
ing short periods of maximal muscular activity.

The rate of muscular work that can be performed immediately
after a person begins strenuous work is approximately 3 to 5 times as
great as the muscular work that can be sustained over long periods of
time. The reason for this is that in the early stages of muscular con­
traction many different sources of energy are available. However,
after the adenylic acid, phosphocreatine, glycolytic and oxygen storage
systems are depleted of stored energy, the only source of energy there­
after is metabolism supported by oxygen delivered continuously to the
tissues. Consequently sustained muscular work is limited by the rate
of oxygen transport to the tissues, whereas the limits of short bursts
of energy are much greater than this because of the readily available
energy stored in highly labile compounds within the muscle cells them­
selves. Butler (42) states that the mitochondria of the cell contain
the oxidizing enzymes, and calls them the power house of the cells.
Each mitochondrion is 2 microns long, and 1/2 micron wide, and contains
about a million protein molecules.

Metabolism of Paraplegic

Whedon (43) states "A new direction of studies of energy expend­
itute which is receiving attention is that toward study of patients
with impaired physical capacities in chronic diseases and of those with
temporary physiological impairment convalescing from acute serious
illness. Studies mentioned previously have primarily had a nutritional
interest,...while present studies are directed toward regulation of the physical stress placed on the patient with subnormal fitness. Investigations are therefore being applied to energy costs of various daily tasks required of patients with orthopedic disabilities and to the search for tests of work capacity from the cardiopulmonary point of view.

"This means that there is both a need to learn how to assess properly the capacity of a patient either limited by chronic disease or convalescent from acute illness and also a requirement for an accurate catalog of the range of energy costs of various activities so that the intensity of effort may be more judiciously selected in accord with the patient's tolerance."

This article was published several months after we had begun this project, but it states our objectives so well that we felt it should be included as being in agreement with our aim in undertaking this survey.

Cooper and Hoen (44) studied 300 patients over a period of five years, most of whom were traumatic paraplegics. They state that the metabolic rate is almost invariably decreased in paraplegics, and values as low as minus 24 percent of predicted normal have been recorded in patients in whom there was no other evidence of hypothyroidism. PBI and blood cholesterol values in such cases have been within normal limits. Although the physiologic basis for a decrease in metabolism in paraplegics is not yet established, the immobilization of paralyzed extremities may contribute to a lower oxygen consumption in such patients.
Rocco and Vandam (45) in discussing the problem of anesthesia in paraplegics remind us of the perplexing physiological alterations that result from transection of the spinal cord. The resultant insult to respiratory and circulatory mechanisms give rise to problems in pulmonary ventilation and circulatory instability. Interruption of sympathetic nerve tracts in the low cervical and upper thoracic cord causes loss of ability to regulate body temperature because of interference with such mechanisms as vasodilation, sweating and shivering. Impulses for temperature control which originate in the thalamus do not reach the appropriate end organs. Warm summer temperatures produce hyperthermia and the volume and oxygen carrying capacity of the blood is decreased to the point where serious circulatory instability and hypotension could result during anesthesia. They advise watching for potential adrenal insufficiency inasmuch as the adrenal may be partially or severely damaged by amyloidosis in paraplegics. This emphasizes the need of awareness of the total damage, rather than just the motor loss incurred in spinal cord transection. We noticed a marked decline in the patient's ability to walk or perform motor tasks during hot weather, and feel that any urging to ambulate at such times could cause serious damage.

Specific Problems in Metabolic Studies of Paraplegics

Ambulation

These patients are, in many cases, unable to ambulate at a regular rate, because the paralyzed lower limbs do not always follow in the same fashion, and the patient may have to re-align himself from time to time, making it impossible to maintain a steady pace. Since most of the patients were able to ambulate only for the duration of the work
period these exercises represent the maximum effort of the patient and
the remaining musculature. In patients with limited musculature, the
effort of ambulation interferes with respiration and some of these
patients have considerably more ability for work, if that work is not
ambulation. For example, occupational tasks requiring arm work that
did not interfere with respiration could be performed more easily than
ambulation. It would be helpful to know how much muscle mass is carry­
ing the load, to draw comparisons with normal subjects.

These patients cannot walk on a treadmill with their crutches,
since the crutches would catch on the flooring and the patient would
fall. Also, because of the need to stop and re-align their limbs, these
patients cannot walk on a surface which is moving toward them at a con­
stant speed. Even with parallel bars, the patients cannot maintain a
steady rate of speed and would fall. Because of this we decided to
have them walk on a floor instead of a treadmill, in order to avoid
falls, and to maintain the patient's sense of security in walking in
familiar surroundings. Some patients could walk only with the aid of
parallel bars, others could walk with crutches, but used different types
of gait (swing through, swing to, 4 point) and thus introduced varia­
tions that could not be altered. Any attempt to change the speed of
gait noticeably, or change the type of ambulation resulted in failure.
Possibly long term training could accomplish these changes, but we were
hampered by heat and lack of time to attempt re-training.

Spasticity

The level of spinal lesion alone is not a sufficiently clear
index of the injury, as some patients have much more muscle spasticity
than others with a similar level lesion. For example, patient H. R. had a similar level of lesion to A.D.A., yet walked only fifty feet in six minutes as compared to 85 feet, due to spasticity. Several newer paraplegics were not studied in this series because of spasticity.

Damage to Heart

Fultz (46) calls attention to possible damage to the heart during exertion, and states that if the heart is diseased, overexertion may precipitate cardiac decompensation and even cause death. This is particularly true when the disease involves the coronary vessels (47) because it is the flow of blood through them which enables the heart to recover from fatigue.

Since it is difficult, if not impossible, to determine the precise state of the coronary vessels, one cannot predict the consequences of physical strain in all cases, and Fultz cautions us not to push older patients too hard. Because arteriosclerosis accompanies age, we must keep in mind that men of 40 or over will have greater difficulty in recovering from physical stress than younger men.

End Point of Fatigue

Some patients were not used in this series because they could not walk for the allotted time, due to fatigue. It would be helpful to know whether they have reached the limit of endurance, or if they lack motivation for the effort required. Bartley and Chute (48) state that fatigue is characterized by a decreased capacity for work, plus changes in the physiological state of the individual as shown by chemical tests, and a feeling of weariness, requiring rest rather than merely a change, as in patients who are "bored". To encourage the patient to continue
work, and yet not harm him is the aim of the training program.

Durnin and Namyslowski (49) used the Max Planck respirometer and analyzed the gas samples by Haldane's apparatus. Because an individual will show quite marked differences in the metabolic cost of lying, sitting and standing at different times, it was decided to determine whether the reason for the variation might be the specific dynamic action of a meal, previous exercise, emotion or some unknown cause.

These authors used ten subjects of each sex, and ran the energy studies on consecutive days and also on widely separated days to study the influence of barometer pressure and changes in temperature. Four separate times of day were used, before and after the midday meal. They also used persons who were and those who were not familiar with the apparatus, and the summary of their conclusion follows:

1. The results showed no significant effect due to either time of day or day.
2. It can therefore be inferred from this experiment that there were no measurable effects due to:
   a. Specific dynamic action of the midday meal;
   b. Changing external temperature and barometric pressure;
   c. Practice in the use of the apparatus; or
   d. Emotion
3. There were no sex differences in the energy expenditure of walking if these results are expressed as Kcal/kg of gross body weight.

Bracing

We are interested also in the effect of various types of bracing upon the work effort required to walk, different types of knee locks, long or short leg braces, pelvic band, and trunk stabilizing corsets or braces. All of these might make it easier (or harder) to ambulate, and
these factors could be studied over a long term program. We did not do it in this study, but hope to be able to get such information as the project progresses.

Training

At least two aspects of training might influence the study, first the length of time of training in ambulation, and second, the state of development of the functioning muscle which remains. This information, too, will require long term study, but will be very useful in determining the most efficient method of restoring the patient to his full capabilities.
METHODS

Ventilation

Measurement and Sampling of Expired Air

The apparatus used is referred to as the Kofranyi-Michaelis (1940) or the Mueller-Franz (1952) apparatus. It is manufactured in the Max Planck Institute for Work Physiology in Dortmund, Germany, and is combined dry-gas meter and fraction sample collector. The apparatus is used widely and is gaining in popularity, and referred to favorably by Durnin and Brockway (35), Passmore and Durnin (19), Insull (50), Whedon (43) and Bard and Ralston (52).

The apparatus is sturdy, and measures the total volume of air passing through it, and at the same time collects a sample of 0.3 or 0.6 percent which is stored in a small bladder for analysis. The principle disadvantage of the apparatus is that it must be used with a mouthpiece or mask, which limits the length of patient tolerance. This was not a problem in the short term studies we carried out, since the total time of using the mouthpiece was 28 minutes.

In our experiment we needed to meet several requirements which are well stated by H. S. Wolff (53):

1. The weight and resistance to respiratory air flow must be sufficiently low to impose only a negligible physiological load, both subjectively and objectively.

2. The integrated sample produced at the finish must be as similar as possible in composition to the mixed contents of a very large Douglas bag, if such had been used.
3. The mechanical construction must be such that the result is independent of the position of the instrument, and sturdy enough to suffer the knocks it might receive while being worn.

Wolff also states in this article: "After an examination of the problem, it was concluded that conventional gas meter technic had probably been taken as far as possible with the Kofranyi-Michaelis apparatus. Wolff has coupled a flow meter with a radio transmitter which bears a reasonable proportionality to energy expenditure.

The favorable comments from reputable laboratories, plus the ease of transporting this apparatus, helped us to decide in favor of the Max Planck respirometer, and this apparatus was used for collection of gas in all experiments.

Apparatus

Plate I (p. 32) illustrates the basic equipment used in collection of gas. The metal frame (1), the Max Planck respirometer (2), the collection bags (3) and the mouthpiece, Douglas valve and tubing (4) are the essential parts of the measuring and collecting apparatus.

The metal frame (1) is on wheels and is very easily guided at the rate of ambulation chosen by the patient, without interfering in any way with progression. Since the entire apparatus is light, it was not difficult to keep up with changes in the gait of the patient, and yet it could be kept close behind the patient, thus keeping dead air space to a minimum. The frame is easily adjusted to any desired height by means of the thumbscrews on each end. The respirometer (2) hung by its two eye hooks and a bumper at the bottom kept it from swinging.

This apparatus provides essentially three things:

a. A centigrade thermometer for checking apparatus temperature,
b. A dry-gas meter which gives total expiratory volume measurements,

c. An aliquoting device for providing either a three or six percent sample of the total expiratory volume, after it has been thoroughly mixed. This device pumps the sample out of the small tube at the end of the machine where it can be collected in a sample bag or bags.

We used seven sampling bags (3), as will be explained later. These were specially constructed for anesthesia and gas sampling purposes so as to minimize gas diffusion. The mouthpiece was fastened to a Douglas valve (4) which in turn was attached to the respirometer by a plastic vacuum cleaner hose. We used the mouthpiece in preference to face masks, which always leaked in spite of considerable trial of various kinds. The Hans Rudolph valve is a low resistance valve which is preferred in energy studies, but was too heavy to be held by the patient. It is commonly used in treadmill studies and supported by a boom, but this could not be done in our type of patients for fear of injury in a fall, so we used the Douglas valve which has somewhat higher resistance, but not significant until ventilation exceeds 100 L/min, a figure that was much higher than any we encountered. This valve is well able to deliver any amount of air needed, and patients were assured of this before its use. Because any type of valve obscures the patients' view of the floor, it became a source of irritation to all of the patients, inasmuch as they use visual contact with the floor in progression, due to loss of touch and proprioception.

The matter of air diffusion from the large hose was of concern, and we used plastic vacuum cleaner hose which has a lower diffusion
rate than the conventional hose that can be purchased, as well as being more easily cleaned and more attractive, and also less expensive. All connections were made tight, cemented where possible.

The respirometer comes from the factory with a correction factor stamped on it, but careful calibration was necessary. Durmin and Brockway (18) give their method of doing this, emphasizing the use of a "pulsatile" flow of air while measuring rather than a steady flow, since the pulsatile flow simulates breathing, and gives a different figure from a steady flow. Insull (50) discusses possible difficulties with the apparatus, and a method of calibration is discussed from the same laboratory by Rieneau and Consolazio (51). We found our machine had a correction factor of 1.05 when measured against the Tissot spirometer, using pulsatile pressure. We also caution regarding the need to re-calibrate the machine at intervals as the readings might change as the machine receives more use. Servicing of the machine is important, seeing that all working parts are free moving and well lubricated. We found Singer sewing machine motor grease in a tube to be a better lubricant than the oil recommended by the manufacturers, and in fact it resembled the grease which was originally on the gliding part of the machine. Oil was used on all other portions, but does not work well on the gliding portion.

Gas Analysis

We used the Scholander apparatus, well known to all workers in the field of pulmonary physiology and accurate to within 0.015 vol. % as calibrated against Haldane apparatus (54). It has the advantage of requiring much smaller quantities of gas, one-half cubic centimeter
Plate I. Photograph of Respirometer, Collecting Bags, Mouthpiece and Portable Frame.
(55) in amount, and handles from zero to 99 percent absorbable gases. The analysis requires 6 to 8 minutes for each sample.

The principle of analysis is the introduction of the gas sample into a reaction chamber connected to a micrometer burette. Absorbing fluids can be introduced to remove carbon dioxide and oxygen without causing any change in the total content of the system. Changes in volume are read as figures on the micrometer and the rinsing fluids and adsorbents are adjusted so as to have the same vapor tension. A water bath surrounds the unit, and a motor drives a counter wheel to shake the apparatus when desired. Zephiran is added to the water to prevent mold.

At the time of analysis, the unknown sample of air has been transferred to an oiled 20 cc hypodermic syringe, the tip of which is sealed by a 3-way stopcock. The stopcock is attached to a short piece of rubber tubing, which is fastened to the Scholander pipette. The pipette has a rubber tip, which fits into the capillary tube of the reaction chamber, under acid rinse solution, and enough air is released to thoroughly wash out the pipette and stopcock. The micrometer is adjusted so that one-half cc of air is drawn into the reaction chamber, and a small amount of acid rinse is drawn in to seal the air sample. This is drawn down by the micrometer so that the meniscus of the air bubble is at a mark on the reaction chamber capillary tubing, at which time the micrometer reading is recorded. The apparatus is tilted so that the carbon dioxide absorbing fluid enters the reaction chamber, and after a brief agitation the micrometer is adjusted to bring the meniscus back to the mark and the micrometer is read and recorded.
again. Then the oxygen absorbing solution is tilted into the reaction chamber and the apparatus is vibrated until there is no change in the meniscus, which is again brought to the mark. The oxygen absorbing reaction takes considerably longer than the carbon dioxide reaction, and must be done last, since the oxygen absorbing solution removes both oxygen and carbon dioxide, whereas the carbon dioxide absorbing solution does not remove oxygen. After oxygen is absorbed, and the reading recorded, the micrometer is turned back until the pink oxygen absorbing solution is at the mark, when the micrometer should read zero or within plus or minus 0.5 of the smallest division.

The apparatus must be thoroughly rinsed between samples to avoid having any absorbing solution in the reaction chamber.

The carbon dioxide absorber is: 100 cc of water, 11 gm of KOH, and 40 mg of potassium dichromate. The oxygen absorber is 100 cc of water, and 6 gm of KOH, mixed just prior to analysis with a powder mixture of sodium hydrosulfite and sodium anthraquinone-beta-sulfonate. The carbon dioxide absorbing solution is stable for several weeks at room temperature; the oxygen absorbing solution should be made up daily in the hypodermic syringe, avoiding contact with air as much as possible. Rubber corks seal the hypodermic needles on the syringes.

Exercise

Eight patients are described in this series, six male and two female. Patients not described are those who were unable to walk long enough to give a useful record, or those who were unable to walk because of fear of the apparatus or feeling of insufficient ventilation,
even at rest. Details will be described in each case history and tabulated for ease of comparison. Similar levels of spinal lesions will be grouped together. Time of injury as well as length of ambulation will be recorded.

It would be desirable for all patients to walk at the same speed and in the same fashion, but this is not possible. Some patients can walk with crutches, some without, and some only on parallel bars. During the period of rest, patients are kept seated whenever possible, but some patients encounter muscle spasm when they begin to stand, and cannot walk for a considerable time (30 to 90 seconds). These patients were kept standing during the resting phase, so that they could begin to walk without delay on command. Because of the need to breathe through the apparatus for eight minutes before collecting samples, in order to "wash" it out, this period of standing no doubt caused a higher resting rate than in those who were seated, but it was considered the most favorable position for accuracy. All patients were encouraged to walk at their maximum speed. In further studies, an attempt will be made to change the speed and find the rate which is most efficient for each patient. Patients wore their usual bracing and this too will be the object of further study to determine the bracing which will be most efficient.

At the time of the experiment, the patient was placed in the resting position (sitting if possible, otherwise standing) and the mouthpiece was introduced. Each patient had been instructed at least once on previous days as to the nature of the experiment, and was assured that the valves were designed to supply him with all the air he could use. He was encouraged to take several deep breaths to feel the
free flow of air, and at that time the apparatus was checked to see that the connections were all tight and that the respirometer was working freely. The bags, which had been stored full of expired air, so as to keep the rubber walls saturated with carbon dioxide, were now emptied by a vacuum pump and clamped off in the collapsed position. The end of the copper tubing was opened so that the aliquoted air would flow to the very end of the apparatus, thus washing it out carefully. The first collection bag was placed farthest away from the machine in order to avoid undesirable mixing of air during collection. The first bag was labelled number 0, the resting sample. After eight minutes of "washing out", the stopcock at the end of the copper tubing was closed, the temperature of the machine was recorded, and the gas meter was read at the same instant that timing was begun by means of a stop watch and the valve opened to bag number 0 for collection of the resting sample of air. At exactly two minute intervals, the collecting bag valve was closed, the next collecting bag opened, and the gas meter reading was recorded. Walking began at the moment of opening bag number 1, and continued through bag number 3. At the time of closing bag number 3, and opening bag number 4, the patient resumed the original resting position and the timing now changed from two minutes to four minutes for each bag until bags number 4, 5 and 6 had been used. At this time the patient was permitted to remove the mouth-piece. The machine temperature was again recorded.

The patient's pulse and rate of respiration were recorded during rest, also after 2 and 6 minutes of work, and after 4 and 12 minutes of recovery, whenever possible. Recording of pulse during work was very difficult, as the arms were used for ambulation. Some pulse
recording device would be a very desirable addition to the equipment as a rough index of level of work and cardiac stress, as well as cardiac efficiency.

As soon as possible, a well mixed sample of air was transferred from each sampling bag into a 20 cc hypodermic syringe, which was well oiled and fitted with a greased stopcock. This required seven syringes, and air was well rinsed out of all dead air space before the final sample was taken. This was done because of the well known tendency of rubber bags to diffuse and be contaminated by room air, even when specially constructed to prevent diffusion as these were.

was permitted during this time. Patients who had to stop and rest were not used, and if any patient stopped to rest, these figures were discarded and the test repeated at another date. In general, the figures represent two "good" exercise trials in each case.

Patient A. D. A. had considerable spasticity and was unable to begin walking from a sitting position without stretching for 30 to 45 seconds, so her resting position was standing. She used axillary crutches, walked a slow 4 point gait. She had no bracing. On her first trial she walked 29 feet in the six minutes, and used very little oxygen above the resting level. She was found to have an M. B. C. of 36 L/min, and was given breathing exercises. Nine days later her M.B.C. was 59 L/min and her distance was 85 feet in six minutes. She did not reach a steady state and oxygen debt was high, not reaching the resting level during the recovery period. Her pulmonary status warrants further investigation.

Patient H. R. had the same lesion level as A. D. A. and also was started from a standing resting position because of spasticity. He,
RESULTS

The figures on the following pages show medical data and oxygen consumption of the patients in this study. The term "aerobic" is used to describe oxygen consumed above the resting level while at work. The term "anaerobic" is used to describe oxygen consumed above resting level during recovery (oxygen debt). During the period of work, the patient ambulated in the manner to which he was accustomed, and no rest was permitted during this time. Patients who had to stop and rest were not used, and if any patient stopped to rest, these figures were discarded and the test repeated at another date. In general, the figures represent two "good" exercise trials in each case.

Patient A. D. A. had considerable spasticity and was unable to begin walking from a sitting position without stretching for 30 to 45 seconds, so her resting position was standing. She used axillary crutches, walked a slow 4 point gait. She had no bracing. On her first trial she walked 29 feet in the six minutes, and used very little oxygen above the resting level. She was found to have an M. B. C. of 36 L/min, and was given breathing exercises. Nine days later her M.B.C. was 59 L/min and her distance was 85 feet in six minutes. She did not reach a steady state and oxygen debt was high, not reaching the resting level during the recovery period. Her pulmonary status warrants further investigation.

Patient H. R. had the same lesion level as A. D. A. and also was started from a standing resting position because of spasticity. He
walked in parallel bars with a swing-thru gait, wearing bilateral long leg braces. In spite of powerful arms, he had great difficulty ambulating for the full time. This points up the great cost of overcoming muscle spasticity, as his speed would undoubtedly be much better without this hindrance. He did not reach a steady state, and did not fully recover the oxygen debt during recovery. His cardiac-pulmonary state was normal.

Patient S. D. walked with Lofstrand crutches, using a swing-to gait. She wore bilateral long leg braces. She did not build up much oxygen debt and stabilized to resting level by the end of the recovery sampling period.

Patient R. W. was not in as good physical condition as S. D., although the level of lesion was the same. He was a very good crutch walker early in the period of his rehabilitation training, but now was only able to ambulate in parallel bars, and appeared exhausted at the end of the work period. He used a 4 point gait, and wore bilateral long leg braces. He did not return to his resting level even after twelve minutes of recovery, and his figures show a false low value inasmuch as all of his oxygen debt was not paid off.

N. Y. is one of three L_1 level patients, whose speed and cal/meter/kg show close grouping. He used Lofstrand crutches and a swing-thru gait, and wore bilateral long leg braces. He reached a steady state during work, and recovered early in the recovery phase.

E. B. used axillary crutches, walked with a swing-thru gait, wore bilateral long leg braces and a Taylor back corset. He reached a steady state and also recovered oxygen debt early.

M. G. walked with Lofstrand crutches, using a swing-thru gait,
and wearing bilateral long leg braces. He did not reach a steady state and did not return to resting level after the recovery period, thus his figures would probably show a higher value if all of the oxygen debt had been calculated. This was not calculated because of his emotional state. He showed antagonism toward the nose clamp, and to having to breathe through his mouth and refused to permit further studies.

A. C. was a very good walker, and to the casual observer might seem to be quite normal, but his muscle weakness did not allow him to push off well, and he had moderate instability at the hips in both sagittal and frontal planes. He used neither crutches nor braces, yet ambulation cost him as much in energy expenditure as normal individuals walking at twice his speed. This disability is of significance in planning his future vocation, inasmuch as it might be easy from superficial observation to expect him to be able to do anything, but he actually has serious limitations. Cardiovascular and pulmonary factors did not limit him, however, he reached a steady state, and recovered quickly.

Energy expenditure figures are recorded in Table II. These figures are calculated on the sum of aerobic oxygen and anaerobic oxygen, in order to have true work values of oxygen consumption. Resting oxygen was not added.

Patients A. D. A., R. W. and M. G. had 91%, 91% and 52% greater oxygen debt than anticipated. This excess "anaerobic" oxygen is probably due to increased muscular activity of dyspnea following the exertion of ambulation.
### TABLE I

Medical Data on the Eight Patients Reported in This Study

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</tr>
<tr>
<td>Weight (kg)</td>
<td>52</td>
<td>64</td>
<td>54</td>
<td>68</td>
<td>66</td>
<td>54</td>
<td>68</td>
<td>77</td>
</tr>
<tr>
<td>Level of Lesion</td>
<td>T₄</td>
<td>T₄</td>
<td>T₁₂</td>
<td>T₁₂</td>
<td>L₁</td>
<td>L₁</td>
<td>L₂</td>
<td>Cauda</td>
</tr>
<tr>
<td>Months since Injury</td>
<td>10</td>
<td>39</td>
<td>4</td>
<td>75</td>
<td>32</td>
<td>4</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Months¹ of Ambulation</td>
<td>6</td>
<td>33</td>
<td>1½</td>
<td>66</td>
<td>24</td>
<td>1½</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Speed² (meters/min)</td>
<td>4.3</td>
<td>2.5</td>
<td>8.2</td>
<td>4.0</td>
<td>18</td>
<td>20</td>
<td>22</td>
<td>69</td>
</tr>
</tbody>
</table>

¹ This figure is the time since the patient began some form of ambulation, not necessarily the same ambulation as at the time of study. In cases of long duration there also were interruptions for hospitalization.

² Speed during ambulation at time of testing.
Plate II. Oxygen Consumption Values Obtained In Patient A. D. A.
Plate III. Oxygen Consumption Values Obtained In Patient H. R.
Plate IV. Oxygen Consumption Values Obtained in Patient S. D.
Plate V. Oxygen Consumption Values Obtained in Patient R. W.
Plate VI. Oxygen Consumption Values Obtained in Patient N. Y.
Plate VII. Oxygen Consumption Values Obtained in Patient E. B.
Plate VIII. Oxygen Consumption Values Obtained in Patient M. G.
Plate IX

A.C. 7.20.59

m. oxygen/min.

2 min. 6 min. 12 min.

rest work recovery

256 265 296

aerobic
anaerobic
Plate IX. Oxygen Consumption Values Obtained in Patient A. C.
TABLE II

Energy Expenditure

<table>
<thead>
<tr>
<th>Patient</th>
<th>cal/min of work</th>
<th>cal/min/kg</th>
<th>cal/meter/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.D.A.*</td>
<td>2000</td>
<td>38.4</td>
<td>8.9</td>
</tr>
<tr>
<td>H. R.*</td>
<td>1780</td>
<td>27.8</td>
<td>11.1</td>
</tr>
<tr>
<td>S. D.</td>
<td>1725</td>
<td>32</td>
<td>3.9</td>
</tr>
<tr>
<td>R. W.*</td>
<td>3355</td>
<td>49</td>
<td>12.3</td>
</tr>
<tr>
<td>N. Y.</td>
<td>2760</td>
<td>41.8</td>
<td>2.3</td>
</tr>
<tr>
<td>E. B.</td>
<td>2450</td>
<td>45.3</td>
<td>2.3</td>
</tr>
<tr>
<td>M. G.*</td>
<td>3800</td>
<td>56</td>
<td>2.5</td>
</tr>
<tr>
<td>A. C.</td>
<td>7330</td>
<td>101</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* These figures are calculated on the basis of oxygen consumption above the resting level, and including oxygen debt.

1 These figures are calculated on the basis of oxygen consumption above the resting level, and including oxygen debt.

2 Using Weir's short method, we calculated on the basis of 5 calories per liter of oxygen.

* These patients did not get out of debt during the 12 minute recovery period, and their true values would be somewhat higher than indicated here.
DISCUSSION

It becomes apparent that there is a tendency to reach similar levels of energy cost for the task of ambulation (Table II). This was true in spite of the fact that there was considerable difference in the length of time of training, and while these are not enough patients to draw definite conclusions, it should be noted that there is a trend in this direction, and see if this holds true as more patients are worked up. It might be possible to establish a period of maximum efficiency, and not prolong the period of training.

Patients with lower level lesions will usually ambulate at less cost than those with higher level lesions, for various reasons, among which might be included the better respiratory apparatus in the lower lesions, the trunk stability with avoidance of unnecessary excursion of the trunk, and the need to bring it back into alignment. Also, the lower level lesions require less bracing, resulting in less weight. These patients will take less steps to cover the same distance, lifting the center of gravity of the body a fewer number of times with a resultant saving of energy. Patients with higher lesions had difficulty in keeping leg alignment in place for the next stance, and had to shift the trunk and shoulders in order to swing the legs into place, which added to their energy cost.

One may conjecture concerning effects of interference with the sympathetic nervous system and results on the vascular bed, with poor response to stress, lack of normal perspiration and shivering, and
proper skin response to work and heat. All these factors may play a role in the inability of patients with higher level lesions to ambulate effectively with such a high energy cost.

Along with the comparisons between paraplegics, energy cost should be compared with normal subjects walking on the level, and Table III shows this comparison. Since the most recent normal figures in the literature were computed on the basis of total oxygen used during work (includes resting oxygen) we used total oxygen figures also in this Table only. We feel that these figures show that energy expenditure of paraplegics in ambulation is very high as compared with normal persons, and in some cases ambulation is achieved at great cost. We are particularly concerned in those patients who did not clear up their oxygen debt in the recovery time, since ambulation involves more than just a function of the muscles of locomotion. If these patients are hypoxic during ambulation, there may be an effect on their coronary vessels and the cardiovascular system as a whole, and damage may result from this exertion. Also, we may be concerned with the effects of this stress upon the endocrine system, particularly the adrenal-cortical hormones. Is it possible that repeated stress may harm the endocrine organs which have already been subjected to much stress from the original injury and the subsequent denervation? We realize that these questions are as yet unanswered, but feel that they should be considered in the overall planning of the physical activities of these patients.

The physiology of exercise has many applications, and most authors have been concerned with work, a form of exercise of social importance and which is receiving considerable attention, such as in industry. In our particular concern for paraplegics we are interested
### TABLE III

*Normal Values According to Bard and Ralston (51)*

<table>
<thead>
<tr>
<th>Name</th>
<th>Walking Speed (m/min)</th>
<th>Cal/min/kg Compared To</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. D. A.</td>
<td>4.3</td>
<td>70 m/min</td>
</tr>
<tr>
<td>H. R.</td>
<td>2.5</td>
<td>50 m/min</td>
</tr>
<tr>
<td>S. D.</td>
<td>8.2</td>
<td>55 m/min</td>
</tr>
<tr>
<td>R. W.</td>
<td>4.0</td>
<td>75 m/min</td>
</tr>
<tr>
<td>N. Y.</td>
<td>18</td>
<td>75 m/min</td>
</tr>
<tr>
<td>E. B.</td>
<td>19.8</td>
<td>85 m/min</td>
</tr>
<tr>
<td>M. G.</td>
<td>22</td>
<td>87 m/min</td>
</tr>
<tr>
<td>A. C.</td>
<td>68</td>
<td>130 m/min</td>
</tr>
</tbody>
</table>

* These figures calculated on total oxygen consumption (resting + aerobic) during work, plus anaerobic (oxygen debt).
in at least two aspects of exercise: first, is the paraplegic exercising enough to get the daily physiological needs, and second, is he exercising to the point where he will do himself harm? We would like to find the level at which the patient gets the needed benefit and yet follow the physician's desire to "do no harm." If this paper will do anything toward establishing this balance, the effort will be well worth while.

At certain levels of injury the patient should be advised against going through the time-consuming program of learning to ambulate, and should conserve his energies for more useful tasks. At other levels he should be persuaded that ambulation is practical, and that this should be a realistic goal. One of our patients was doing very slow ambulation, and the studies convinced her that she could and should try harder, and has improved noticeably within a short time. Another patient was advised not to try to ambulate, but persisted in doing so, and was placed in the hospital with acute heart failure and pulmonary edema.

Gordon (3) states that in some patients a swing-thru gait on a continuous basis produces exhaustion analogous to that of a normal individual performing a 440-yard run. In the paraplegic there is much more damage than merely partial paralysis and possibly this type of effort is not only physically impractical, but definitely harmful. He should stand at least an hour a day for the physiological benefits of weight bearing (56), but seek another more realistic means of progression. We feel that this study, when carried on into the future will provide information that will help the decision to be made early in the rehabilitation phase, and that the training program will achieve its height of efficiency when this information is considered in the decision of the patient's potential for accomplishing certain tasks.
Sanders (35) states that if a patient has normal neck muscles and sufficient strength in his fingers to grasp crutches, with enough power in the anterior deltoids or pectorals to swing the crutches forward, he can walk, although his trunk and both legs are paralyzed.

We feel that this does not consider that the muscles used in ambulation here are also used for respiration and creates very real difficulties for the patient. It is interesting to note, that the Editor of the Year Book added a footnote in which he states that there are few, if any, follow up studies to show that after training paraplegics continued to walk. He also states that patients should be encouraged to walk as a means of exercise, rather than as a means of locomotion.

Munro (36) lists the foundation of rehabilitation as:

1. Early accurate factual diagnosis based on the pathology that is present.
2. Elimination of uncontrollable spasm.
3. Reduction of G. U. infection to minimum.
4. Maintenance of a bladder that is of normal size and capacity, and that functions on a reflex or better basis.
5. The same functional requirements for the bowel.
6. The maintenance of full motion in all joints.
7. The development of maximum capacity of the shoulder girdle, arm and hand muscles.
8. The ability to balance in the absence of peripheral sensations.
9. Finally, continued interest and stimulation by the doctor.

After laying the foundation, he lists the goals of rehabilitation as:

1. Self-care
2. Social life
3. Employment
4. Control of bladder and bowel
5. Ambulation
6. Sexual capacity
We note here that Munro places ambulation near the bottom of his list and concedes that other things are of more importance. He states: "...perhaps the most difficult to learn of all the technics of rehabilitation is ambulation." He finds that it is even more difficult to persuade the patient to practice and maintain this skill once he is outside the influence of his physician, and that it requires the most eloquent reasoning to convince the patient that weight bearing and upright motion are the best insurances against genito-urinary infection and urinary stones. He states that if the patient fails to continue to walk that this is evidence of a certain degree of rehabilitory regression that may mark the first step to a return to invalidism. He feels that this is difficult to do in the face of the habit we all have acquired of riding in an automobile instead of walking on our own two feet, and the lure of comfort and lack of effort required to use a wheelchair may be difficult for all to resist and impossible for some.

However, there is evidence that while ambulation is a worthy goal it may not be necessary to fulfill the physiologic needs of the patient; and Abramson (56) feels that one hour of standing daily will prevent osteoporosis and help prevent urinary calculi and infection.
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