Maximal Oxygen Intake as an Objective Measure of Cardio-Respiratory Performance

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During the Second World War this laboratory studied the relationships between performance in its broadest sense and biological stress, with emphasis on nutrition (1-6). An effort was made to assemble a battery of tests which would sample the several important components of physical performance (7). The details of the psychomotor tests have been presented elsewhere and the experience with it has been reviewed (8). These tests were fitted into a larger concept of performance capacity and applied originally to the problem of thiamine requirements (9-11).

Early in this program, it became apparent that procedures employed by physiologists to test work performance or the performance of an important physiological system limiting work capacity were open to serious criticism. On one hand, motivation was an important factor in the performance tests using exhaustion as an end point (12, 13). On the other hand, skill in performing the physical task was an important but not necessarily a constant factor affecting tests based on the response to a fixed task (14).

The maximal oxygen intake appeared to offer the possibility of determining with precision one of the limiting factors in endurance performance characterized by a high level of energy expenditure. The previous work on this measurement, reviewed by Simonson and Enzer (15), suggested that test conditions could be found which would eliminate both motivation and skill as limiting factors. It is the purpose of this paper to describe the technique of maximal oxygen intake used in this laboratory, its limitations and its usefulness in longitudinal experiments. By longitudinal experiments, we refer to the situation in which the investigator wishes to examine the effects of an imposed experimental condition such as a physical conditioning program, an experimental diet or a new environmental condition. In such experiments each subject serves as his own control and passes through a control period, an experimental period and where it serves a purpose, a recovery period. This paper will concern itself principally with the problems of comparing the subject with himself under different conditions. The problems involved in comparing one group with another will be treated in a separate paper, the substance of which has already been presented in preliminary form (16).

Data reported here were obtained in several experiments. A total of 42 conscientious objectors were studied under a variety of stresses (1-3, 5, 6). Twenty-seven soldiers, volunteers from the test pool of the Quartermaster Corps at Fort Lee, were subjects in relatively short-term studies on acute caloric restriction (17). In addition there were 46 volunteers recruited from the student body of the University of Minnesota. All subjects were males between the ages of 18 and 35 who had passed a rigorous physical examination and were considered to be in good health. There was a large difference between subjects in the ability to run (a few were members of the varsity track team) as
Table I. Use of the Harvard Fitness Test to Predict the Lowest Grade Which Will Result in a Maximal Oxygen Intake

<table>
<thead>
<tr>
<th>Grade, %</th>
<th>Harvard Fitness Test</th>
<th>Time of run, sec.</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>130-190</td>
<td>40-60</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>100-300</td>
<td>55-80</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>240-300</td>
<td>80-92</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>300</td>
<td>95-105</td>
<td></td>
</tr>
</tbody>
</table>

well as a large difference in body build and composition.

General Conditions and Methods

All tests were carried out in air-conditioned suites maintained at 78°F ± 2°F and 45-60% relative humidity. Work was carried out on a motor driven treadmill at speeds and grades specified below. Expired air was collected in balanced spirometers. Modified Loven respiratory valves were used. Connections between valves and spirometers were 32 mm in diameter. Work up to 1946 was carried out with a mouth piece which had a lumen diameter of 19 mm. After 1946 a mouth piece with a 38 mm diameter was used with a redesigned valve. In 11 subjects, the use of the new large mouth piece and valve resulted in an increase of 4% in oxygen consumption, of 9% in ventilation, and an increase of 0.01 units in the R.O. In this paper the standards are taken from data obtained with the large mouth piece and valve. Data from longitudinal studies are quoted using both large and small mouth pieces.

Maximal Oxygen Intake: Procedure. The subjects were asked to come to the Laboratory for a minimum of 3 days and occasionally for as many as 5 days to establish the work loads necessary to produce a maximal oxygen intake. The subjects were allowed a light breakfast. However, if auxiliary measurements (such as recovery pulse rate, oxygen debt, etc.) were made, the subjects came to the Laboratory without breakfast. Subsequent visits were dictated by the type of study the subject was participating in.

On the first visit the subject was familiarized with the respiratory apparatus and performed the treadmill version of the Harvard Fitness Test (12). From the score on this test, it was possible to make a reasonable estimate of the correct grade which would yield a maximal oxygen intake. The experience of this Laboratory is summarized in Table I.

On the second visit the subject first walked at 3.5 mph on a 10% grade. The duration of this treadmill walk varied from 10 minutes to 1 hour. This warm-up time was kept constant for each experimental situation. Within 5 minutes or less of completing this walk, the subject started running at 7 mph on the grade previously selected. The gas collection apparatus was flushed at least twice. The last flushing was completed at about 1 minute and 30 seconds of running. Exhaled air was collected between 1 minute and 45 seconds and 2 minutes and 45 seconds of running. The subject was stopped at the end of 3 minutes and postexercise observations were begun.

On the third visit to the Laboratory, the procedure was repeated with the subject running on a grade 2.5% higher than had been employed on the second visit. If the two oxygen intakes were different by less than 150 cc/min. or 2.1 cc/kg/min. the working conditions used were considered to have elicited a maximal oxygen intake. If a larger positive difference occurred, a fourth visit to the Laboratory was required and the 3-minute run was carried out at a grade which was again increased by 2.5%. The procedure was repeated until two grades were found which resulted in oxygen intakes which met the established criterion.

RESULTS

Selection of Test Conditions. The test conditions were chosen with the requirements of performance under stress in mind. With the debilitated man, the shortest time of run must be used that is consistent with obtaining a maximal oxygen intake and efficient operation. The duration of the run was placed at 3 minutes, which is the shortest running time which allows for collection of expired air a full 1 minute after the peak oxygen intake is reached and in addition allows a small factor of safety (perhaps 30 sec.). The expired air collection time of 1 minute 45 seconds to 2 minutes 45 seconds is supported by the data of Robinson (18) indicating that a plateau had been reached by 1 minute 30 seconds of running under conditions which would elicit a maximal oxygen intake. Data obtained in this Laboratory confirmed this observation. A collection of expired air between 2 minutes 45 seconds and 3 minutes 45 seconds of running in 10 experiments gave a mean oxygen intake of 3.45 l/min. which is not different from the mean value of 3.48 l/min. found during the period 1 minute 45 seconds to 2 minutes 45 seconds.

Two methods of attaining the maximal oxygen intake were studied. Using the first method, the treadmill grade was set at zero and the subjects were asked to carry out the 3-minute run on successive days. Each day the speed was increased until the oxygen intake during the standard collection time had reached a plateau. Examples of the results are presented in figure 1. It will be noted that two of the subjects presented in this figure demonstrated

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The authors are indebted to Dr. O. Reynolds of the Office of Naval Research for a limited supply of these mouthpieces.
a plateau of oxygen intake with increasing speed. The other two subjects failed to do this. The reason appeared to be the inability of the men to run fast enough to keep up with the treadmill at the speed of 12 miles an hour. This was true of 4 out of the 13 men studied. The other nine men demonstrated a satisfactory oxygen intake plateau.

In the second method, the speed was held constant and the grade increased by 2.5% until the oxygen intake became constant. Seven miles an hour was chosen since it is the slowest speed at which all subjects appear to be forced to maintain a running stride (a few subjects will break their stride at 6 mph) and it is slow enough to insure that a wide range of capacity can be tested satisfactorily. A few illustrative results are presented in figure 2. Our experience with the procedure of increasing the grade with the motor driven treadmill to attain a maximal oxygen intake.

**Criterion for Demonstration of the Maximal Oxygen Intake.** Inspection of figure 2 makes it clear that before the maximal oxygen intake is attained there is a large increase in oxygen consumption as a result of increasing the grade 2.5%. In order to learn something about the magnitude and limits of this change, the oxygen intake was determined under standard test conditions in 13 subjects at two or more grades below the grades resulting in the oxygen intake plateau. The mean oxygen intake increment for a 2.5% increase in grade on 30 occasions was found to be 299.3 with a standard deviation of 86.5 cc/min. or 4.18 & 1.07 cc/kg/min. The range was 159 to 470 cc/min. or 2.2 to 5.9 cc/kg/min. It appears, then, that if one insists that two consecutive determinations separated by a grade of 2.5% differed by less than 150 cc/min. or 2.1 cc/kg, there is small chance of making an error in deciding that the maximal oxygen intake had been reached. On the other hand, applying these limits will result in asking subjects to run at a grade which is one step higher than necessary in about 10% of the cases studied. The standard deviation of the differences between the first and second grade was 114 cc/min. and 1.60 cc/kg/min. Both criteria are 1.3 standard deviations of the distribution of differences.

**Effects of Some Test Conditions on the Maximal Oxygen Intake.** Twelve men were used to study certain test conditions. The
TABLE 2. EFFECT OF SEVERAL TEST CONDITIONS ON THE MEAN MAXIMAL OXYGEN INTAKE OF 12 SUBJECTS

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Max. O₂ Intake/min.</th>
<th>Mean Diff.</th>
<th>Level of P, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Exp.</td>
<td></td>
</tr>
<tr>
<td>5-min. warm-up</td>
<td>3.64</td>
<td>3.56</td>
<td>-0.09</td>
</tr>
<tr>
<td>Room temp., 90°F</td>
<td>3.75</td>
<td>3.65</td>
<td>-0.15</td>
</tr>
<tr>
<td>Food (750 Cal.)</td>
<td>3.64</td>
<td>3.61</td>
<td>-0.04</td>
</tr>
<tr>
<td>Test treadmill speed 8 mph</td>
<td>3.75</td>
<td>3.71</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

For each new condition, the maximal O₂ intake was determined under standard conditions the day before the condition was examined. Standard conditions consisted of 60 min. of warm-up at 3.5 mph on a 10% grade, a test treadmill speed of 7 mph, a room temperature of 78°F and 50% relative humidity and no breakfast for the subjects. Significance of the difference between the control and the experimental observation was tested with t test for paired variates.

Data are given in Table 2. Before each condition was studied a new determination of maximal oxygen intake was carried out under standard conditions. On the following day one factor was altered and the test repeated. A period of several weeks separated each test and this interval appears to account for the differences in the control values. The data demonstrated that a 5-minute warm-up time is inadequate and that control of environmental temperature is important. On the other hand, a small meal appears to have little or no effect on the maximal oxygen intake. The effects of speed at the same grade were examined in an effort to throw some light on whether the test was independent of skill. The increased speed and resulting change in stride resulted in no significant change in oxygen intake (Table 2). This experiment was repeated on eight other individuals. The mean maximal oxygen intake under standard conditions was 3.68 and at a speed of 8 mph was 3.62. It appears that small differences in the speed of running and therefore small variations in running style, which result in variations in steps per minute, have little or no effect on the maximal oxygen intake.

We can, however, study other methods of increasing the 'maximal' oxygen intake as produced under the standard test conditions used here. The effect of bringing new muscle groups into action can be studied by providing arm work in addition to the leg work required by the treadmill run. An ergometer which could be pedaled by hand was mounted over the treadmill and one of us (E. B.) undertook to acquire the skill necessary to operate the ergometer while running at speeds and grades which would produce a maximal oxygen intake. Figure 3 thus exhibits the results obtained when the subject ran at 7 mph in three increasing grades with and without arm work. It will be noted that the use of the arms increased what had been designated the maximum oxygen intake by 200 cc/min. or more. The experiment was repeated holding the grade constant at 1.5% and increasing the speed. Again the arm work plus running resulted in an oxygen intake which was larger than that obtained by running alone. The arm work was performed at a rate of 550 kg m/min. which resulted in an oxygen intake of 1270 cc/min. when performed alone. It is clear that only a fraction of this requirement was met during the combined work experiments. This may be due in part to the subject's inability to completely avoid partial support by the arms when engaged in simultaneous arm and leg work. It does follow, however, that the 'maximal oxygen intake' can be influenced by the mass of muscle employed to perform the work.

In this connection it is of interest to mention one further observation. Nine men were able to achieve an oxygen intake plateau with the treadmill grade set at zero and the work increased by increasing the speed. It was found that the maximal oxygen intake produced by increasing the speed was 189 cc/min. smaller than that produced by raising the grade. It is quite possible that this difference in the apparent maximal oxygen intake can be accounted for by the use of accessory muscles in grade running which are not employed in running on the level.

Maximal Oxygen Intake and Longitudinal Studies of Physiological Stress. The experience of this Laboratory in the application of the maximal oxygen intake procedure to longitudinal experiments in which each subject serves as his own control is summarized in Table 3. It will be noted that the maximal oxygen intake is reasonably sensitive to a number of stress situations.

These experiments have shown that the maximal oxygen intake is a procedure which
can be efficiently used in longitudinal studies in which a biological variable is to be observed for a matter of days or weeks rather than minutes or hours. Time should always be allowed to establish new work conditions which will elicit a maximal oxygen intake after deterioration has occurred during the stress. It is of some interest that in the presence of the deterioration produced by 6 months of semistarvation, the subjects were still able to push themselves enough to establish a new plateau of oxygen intake at substantial reduced work levels (2). Thus, it was possible to demonstrate that the loss of the maximal oxygen intake was due to reasons other than the loss of motivation.

In the presence of a less severe decrease of performance capacity due to stress, it is feasible to combine the maximal oxygen intake procedure with measurements designed to study the physiological response to a fixed task. This has been done by adding determinations of blood lactate, oxygen debt and recovery pulse rate during the postexercise period after the subject has run 3 minutes at the lowest grade which produced a maximal oxygen intake. These work conditions have been held constant throughout stresses which resulted in mild deterioration (3, 4, 16). Men have been able to complete this work task in the presence of a 17% loss of maximal oxygen intake (3). It should be kept in mind, however, that there is good reason (16) to believe that repeated bouts of running on the treadmill result in improved skill for performing the task and reduced oxygen cost. If the work load chosen is close to work loads which fail to elicit a maximal oxygen intake in a given subject, then a substantial improvement in skill in running on the treadmill could result in a reduction of the apparent maximal oxygen intake. It is always wise to test the adequacy of the work conditions for eliciting a maximal oxygen intake in prolonged longitudinal experiments where the grade is fixed. Such a situation could result in a lower oxygen intake which was not the result of any loss of performance by the cardiorespiratory system.

The experiments referred to in table 3 illustrate two of several mechanisms for decrease of maximal oxygen intake. Bed rest (3) would appear to cause a decrease due almost entirely to cardiovascular function while semistarvation illustrates the effects of loss of muscle (active tissue) in exercise in addition to some loss of cardiovascular capacity. It is quite clear from the experience with semistarvation (2) and the study of the effects of body dimensions and body composition in normal young men (16) that in any longitudinal experiment in which there may be a change in muscle mass, efforts should be made to describe the extent of this change by methods which have been discussed in detail elsewhere (19).

The number of subjects who can be examined with a technique in a single day is an important point in planning longitudinal experiments. In this Laboratory, it has been possible for a single observer to collect the expired air for maximal oxygen determination in 14 subjects in the morning and to analyze the gas in the afternoon. Subjects may be scheduled every 15 minutes. This can be accomplished if two treadmills are available so that one subject may be warming up while a second is actually performing the test. If only one treadmill is available, the warm-up may be done over a prescribed course outside of the laboratory.

**Reliability of the Maximal Oxygen Intake.** The reliability of the maximal oxygen intake measurement was examined by determining the coefficient of reliability for 28 duplicate determinations of oxygen intake obtained at the lower grade which would elicit a maximal oxygen intake. This coefficient was found to be 0.95. The standard error of measurement was 0.84 cc or 2.4% of the over-all mean.

It is sometimes desirable to study the effects of dietary restriction over a long period of
However, there has been some question whether the reliability and sensitivity of the maximal oxygen intake measurement would allow its useful application to problems of stress in which the changes in performance capacity are small when compared to those found in the presence of cardiovascular or pulmonary disease.

It is clear from the study of test conditions that the test must be rigorously standardized in terms of the work task, the length of time and intensity of the warm-up period and the environmental temperature. When this is properly done, it becomes possible to detect very small changes in oxygen intake. Thus a difference of 168 cc between two measurements in one man will occur on only one occasion in twenty by chance alone.

The finding that the use of arm work increases the maximal oxygen intake confirms the observation made by Astrand (25), on the one skier studied by Christensen and Hogberg (26), that skiing in which ski poles are used results in a higher maximal oxygen consumption than running. This supports the thesis (16, 17) that an important determinant of the maximal oxygen intake is the mass of muscle employed in performing the task used to elicit the maximal oxygen intake. It will be remembered that after the maximal oxygen intake has been reached changes in either the speed of the treadmill or the grade do not change oxygen intake. It would appear to follow, then, that as long as changes in skill in grade running did not change the mass of muscle employed for this purpose, the maximal oxygen intake is independent of skill.

An important consideration is the criteria for attaining a maximal oxygen intake. In the past, this has varied. Knipping (22) and Herbst (21) used increasing work loads which resulted in an oxygen plateau but neither author defined a precise criterion for the attainment of the plateau.

Astrand (25) used the level of lactate in the blood in many cases and in others the establishment of an oxygen intake plateau. This investigator provided a criterion for attainment of the maximal oxygen intake in terms of the concentration of lactate in the blood but not in terms of oxygen intake. The group at the Harvard Fatigue Laboratory and at the

<table>
<thead>
<tr>
<th>Condition Studied</th>
<th>Time of Stress</th>
<th>O₂ liters/min.</th>
<th>Observed Decrease</th>
<th>Per Cent Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed rest (3)</td>
<td>21 days</td>
<td>3.85</td>
<td>3.18</td>
<td>0.67</td>
</tr>
<tr>
<td>Malaria (5)</td>
<td>10 days</td>
<td>3.69</td>
<td>2.95</td>
<td>0.74</td>
</tr>
<tr>
<td>Acute starvation  (4)</td>
<td>4.5 days</td>
<td>3.45</td>
<td>3.10</td>
<td>0.26</td>
</tr>
<tr>
<td>Minimum calories* (16)</td>
<td>12 days</td>
<td>3.50</td>
<td>3.32</td>
<td>0.18</td>
</tr>
<tr>
<td>Semistarvation† (2)</td>
<td>6 months</td>
<td>3.11</td>
<td>1.05</td>
<td>1.16</td>
</tr>
</tbody>
</table>

* 580 Cal/day. † 1600 Cal/day.

time (1). In this Laboratory, 12 subjects were maintained on the same control diet and exercise schedule for some 14 months. The men were subjected to short stress periods such as work at 120°F, acute starvation, etc., separated by adequate time intervals. However, the maximal oxygen intake measured during the control periods remained remarkably constant. The data are presented in Table 4. The variance in the data was analyzed and it was found that the differences between individuals was highly significant and the trend over time was without significance. It was estimated that in the population from which this group was drawn, 18.7% of the variability was random, 80.5% was accounted for by differences between individuals and less than 1% was accounted for by day to day variability.

Discussion

The classical work of Hill (20) has demonstrated that there is an upper limit to the capacity of the combined respiratory and cardiovascular system to transport oxygen to the muscles. There is a linear relationship between oxygen intake and work load until the maximum oxygen intake is reached. Further increases in work load beyond this point merely result in an increase in oxygen debt and a shortening of the time in which the work can be performed. The early investigators realized that this situation could be used to study both cardiovascular (21) and respiratory (22) performance in the presence of diseases of these systems. It has been demonstrated that the maximal oxygen is markedly affected by the presence of these diseases (21–24).
TABLE 4. FIVE REPETITIONS OF THE MAXIMAL OXYGEN INTAKE ON 12 MEN OVER A PERIOD OF 1 YEAR *

<table>
<thead>
<tr>
<th></th>
<th>C.</th>
<th>D.</th>
<th>E.</th>
<th>H.</th>
<th>M.</th>
<th>A.</th>
<th>B.</th>
<th>W.</th>
<th>S.</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/30/45</td>
<td>3.33</td>
<td>3.59</td>
<td>3.77</td>
<td>3.43</td>
<td>3.57</td>
<td>3.71</td>
<td>3.86</td>
<td>3.48</td>
<td>3.08</td>
<td>3.29</td>
</tr>
<tr>
<td>12/7/45</td>
<td>3.28</td>
<td>3.74</td>
<td>3.89</td>
<td>3.42</td>
<td>3.57</td>
<td>3.62</td>
<td>4.02</td>
<td>3.43</td>
<td>3.62</td>
<td>3.12</td>
</tr>
<tr>
<td>Mean</td>
<td>3.18</td>
<td>3.60</td>
<td>3.74</td>
<td>3.42</td>
<td>3.58</td>
<td>3.66</td>
<td>3.65</td>
<td>3.47</td>
<td>3.58</td>
<td>3.20</td>
</tr>
</tbody>
</table>

* The men lived in the laboratory dormitory and followed an exercise schedule of 1 hour's walk on the motor driven treadmill plus laboratory chores 6 days a week.

Trudeau Foundation felt that the maximal oxygen intake had been attained if the work conditions were severe enough to exhaust the subject in less than 5 minutes. In well-motivated subjects, such as champion athletes (27) or men who have undertaken intensive physical training (28, 29), this assumption appears to be justified. On the other hand, in older men (18) and in subjects who have become fatigued, discouraged or debilitated due to experimental conditions or diseases, there is good reason for not trusting the subject's willingness to push himself to the point at which a maximal oxygen intake is elicited. The safest procedure is to insist on proof of attainment of the maximal oxygen intake in all cases. In our experience, there are occasional 'normal' subjects who do not care to push themselves to the point which produces the maximal oxygen intake.

The use of a single period of expired air collection between 1 minute 45 seconds and 2 minutes 45 seconds of running may result in apparent declines in the maximal oxygen intake during a stress which are in reality only the reflection of the fact the rate of increase in the oxygen intake is slower than normal. In this situation it will still be correct to interpret the reduction of the maximal oxygen intake as indicating an impairment of the cardiovascular-respiratory system.

In the past, much emphasis has been placed on pulse rate changes during or after work as a criterion of 'fitness.' A tacit assumption has been made that factors which produce a high work rate (or recovery pulse) are accompanied by inefficient cardiovascular performance. It is, therefore, interesting to note that marked increases in aerobic work pulse, associated with the mild dehydration and acidosis of starvation, may be accompanied by only a small loss of maximal oxygen intake (4). In contrast, no change in the aerobic pulse rate during semistarvation (2) was associated with a very large loss of maximal oxygen intake. The expected situation in which a marked increase in aerobic work pulse and a substantial loss of maximal oxygen intake were found has been recorded during studies of the effects of bed rest (3).

SUMMARY AND CONCLUSION

The treadmill conditions which are best adapted to eliciting a maximal oxygen intake have been studied. It was shown that using a constant speed (7 mph) and increasing the grade in steps of 2.4% is more satisfactory than using a constant grade and increasing the speed. Expired air was routinely collected between 1 minute 45 seconds and 2 minutes 45 seconds of a 3-minute run. It was shown that the oxygen consumption at this time had reached an apparent steady state by examining the oxygen consumption for the following minute of running. The increase in oxygen consumption, associated with an increase of 2.5% grade (below the maximal oxygen intake) is approximately 300 cc/min. If the oxygen intake at two different grades differs by less than 150 cc/min. or 2.1 cc/kg of body weight per minute, it can safely be assumed that a maximal oxygen intake has been attained.

Increasing the treadmill speed from 7 to 8 mph, with grade set at a level which elicited the maximal oxygen intake, failed to increase the oxygen consumption. A light meal had no effect on the maximal oxygen intake. The room temperature and the time of the warm-up period before the maximal oxygen intake determination were shown to influence the apparent maximal oxygen intake. Increasing the working muscle mass by simultaneous running and arm work produced a definite increase in the apparent maximal oxygen intake. It was
concluded that the maximal oxygen intake is only maximal for specified working conditions.

The coefficient of reliability was found to be 0.95 in 69 test-retest determinations and it was shown that the test results remain very constant over a period of 1 year in men whose physical activity did not vary widely during this time interval. The application of this procedure, which is independent of subject’s motivation and skill in grade running, to longitudinal investigation of effects of certain biological stresses was discussed.

REFERENCES
17. Unpublished work, Laboratory of Physiological Hygiene.