COMPARISON OF AIR AND WATER DISPLACEMENT FOR MEASURING THE SPECIFIC GRAVITY OF THE HUMAN BODY

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Richard Henry Gnaedinger

1960

COMPARISON OF AIR AND WATER DISPLACEMENT FOR MEASURING THE SPECIFIC GRAVITY OF THE HUMAN BODY

By

Richard Henry Gnaedinger

AN ABSTRACT

Submitted to the College of Agriculture
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Animal Husbandry

1960

Approved A. M. Pearson

ABSTRACT

The purposes of this experiment were to study further the air displacement method for measuring body volume in man and to compare the results obtained with those by water displacement.

The apparatus used for air displacement consisted of two large chambers that were connected to a mercury manometer and a vacuum pump by a suitable arrangement of stopcocks and pipe fittings. The subject was placed in one chamber and a known vacuum was drawn on the other. The pressures were then equalized between the chambers and body volumes were determined from the pressure-volume relationship according to a modification of Boyle's law ($PV = P'V'$). The temperature of each chamber was recorded with a thermistor and incorporated into the calculation of body volume according to Charles' law ($VT' = V'T$). The relative humidity of the air in the animal chamber was recorded with an electric hygrometer and the observed pressures were corrected for vapor pressure of water according to Dalton's law of partial pressures ($P_{gas} = P_{total} - P_{water}$). The air in the evacuation chamber was kept dry with calcium chloride desiccators.

For the water displacement method, the subjects were submerged in a swimming pool and their weight was recorded with a Sanborn Twin-Viso Recorder. A load cell was used to pick up weight which was in turn amplified by a Strain Gauge to the Recorder. This instrument was used to get a continuous record of weight as the subjects breathed

through a snorkel while submerged. The underwater weight of each subject at maximum expiration was used to compute body volume. A value of 1.450 liters for residual air volume was used for each subject. Body volume was computed according to Archimedes' principle (a solid submerged object loses weight equal to the volume of water it displaces).

The results of the specific gravities obtained by each method on 26 human male subjects showed a correlation coefficient of 0.361. The values obtained by air displacement showed a greater variation than those in water. The results indicated an advantage in correcting for the relative humidity of the air in the animal chamber. The major difficulties in the air displacement technique were those of obtaining representative values of temperature and relative humidity of the air in the animal chamber. The major source of error in the water displacement technique was the limiting accuracy of the values for underwater weight. Another possible source of error was the inability of the subjects to expel the same proportion of air from their lungs.

COMPARISON OF AIR AND WATER DISPLACEMENT FOR MEASURING THE SPECIFIC GRAVITY OF THE HUMAN BODY

By

Richard Henry Gnaedinger

A THESIS

Submitted to the College of Agriculture
Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Animal Husbandry

1960

ACKNOWLEDGMENTS

The author is grateful to the Departments of Animal Husbandry, Health, Physical Education and Recreation, and Physiology and Pharmacology for supplying the necessary space and materials for the completion of this project. He is also grateful to Michigan State University and the Michigan Agricultural Experiment Station for their financial assistance.

The author is especially grateful to Dr. A. M. Pearson and Dr. R. W. Luecke for their technical assistance in the project and for supervising the curriculum of the author. He is also grateful to Dr. E. P. Reineke, Dr. H. J. Montoye, and Dr. W. D. Van Huss for their technical guidance and assistance in the project. Thanks are expressed also to Dr. J. L. Dye for his technical advice, and to Mrs. Bea Eichelberger for her typing of this thesis. The author is also grateful to G. Harrington for his assistance in analyzing the data.

TABLE OF CONTENTS

INTRODUCTION

The composition of the human body has always been a subject of much interest to research workers in the field of human biology. Various methods have been devised and used to estimate composition, but only a few of these have proven reliable. Perhaps the most versatile and convenient method is the determination of specific gravity of the intact body, which is in turn related to its composition. The essence of this method is its dependence upon an accurate measurement of body volume. Various designs of apparatus have been used to accomplish this difficult task. However, all were designed to either measure the amount of water or air that the subject displaced. The underwater weighing technique of water displacement has been widely used as the standard for measuring the body volume of living human beings. This method is not applicable to live farm and laboratory animals, so various methods of air displacement have been used to measure their volumes. Air displacement has also been applied to human subjects, but most results obtained have not been very reliable. If the details of the air displacement technique could be refined enough to obtain reliable results, it would be the method of choice for measuring body volume, because of its convenience and versatility.

The purpose of the experiment reported herein was to study further the method of air displacement and to compare the results of specific gravity obtained on adult human beings with those obtained by underwater weighing.

REVIEW OF LITERATURE

History of Specific Gravity

Specific gravity is defined as that number which indicates how many times heavier a substance is than an equal volume of another substance taken as a standard. It is one of the first fundamental principles of hydrostatics, and its discovery is ascribed to Archimedes, about 287 B.C. (2). He reportedly discovered specific gravity by observing the overflow of water that resulted when he partially immersed himself into a tub of water. From this, he concluded that the amount of water displaced must be equal to the volume of that part of his body that was submerged. From subsequent observations on the weightlessness of his submerged leg, Archimedes further concluded that a solid floating or submerged body loses weight equal to that of the volume of water it displaces. Hence, the principle of specific gravity was developed.

The discovery of this principle made possible the characterization of many solid objects, both inert and animate, with respect to volume, density, and specific gravity.

Application of Specific Gravity to the Human Body

Water displacement. - Although specific gravity was discovered and subsequently used to characterize inert objects, it was not applied to living animals until the eighteenth century. In the year 1757, Robertson (12) used a method of water displacement to find the specific gravity of 10 very slim, medium sized men. The men were allowed to submerge in a wooden cistern (78 x 30 x 30 in.) filled with water, and their body volumes determined from the volume of water that each displaced. The results of his specific gravity studies showed that every man except one was lighter than his equal bulk of water, which indicates a specific gravity of less than 1.

Subsequent to Robertson's experiment, a whole century elapsed before human specific gravity received any further study. Since then, this subject has been investigated by many workers. Most researchers before 1940 used water displacement to find body volume. The operating procedure of this method is quite simple. The subject is slowly lowered into a cylindrical tank filled with water, until he is completely submerged. The volume of water displaced is found by measuring the overflow or by noting the rise of the water level in the tank. This volume must then be equal to the volume of the subject since a submerged object displaces a volume of water equal to its own volume. With knowledge of this figure and the weight of the subject in air, specific gravity is calculated by the equation:

$$\text{Specific Gravity} = \frac{\text{Wt. in air}}{\text{Volume}}$$

This is the basic equation for calculating specific gravity. An accurate weight of the subject in air is usually easy to obtain; whereas, volume is not. Herein, lies the greatest problem of finding human specific gravity.

The above method will serve to illustrate the problems commonly encountered in a volume determination. The immersion medium, usually water, should be kept as near to body temperature as possible (10, 17). This may be difficult or impossible to do with a small tank. Furthermore, when the same water is used for numerous subjects, its density may be changed enough to cause some error (17). When the displaced water is collected in a measuring flask, the accuracy of the resultant volume will depend upon the calibration of the flask (2). Similarly, when volume is determined from a calibrated rise in water level, the accuracy of the volume will depend upon the accuracy of the calibration (14). The latter two problems afford common sources of error which are difficult to eliminate.

Perhaps the greatest problem in finding body volume is that of overcoming the errors caused by the amount of air in the subjects lungs at the time of immersion. This less apparent problem was recognized by early workers, as Ziegelroth (2) in 1896 obtained a 3 liter increase in body volume of his subjects on deepest inspiration as compared to deepest expiration. If no correction is made for the amount of air in the lungs, the resultant body volume will cause a considerable error in specific gravity.

Many of the earlier workers apparently were unable to overcome these problems as their results were so variable as to be meaningless (2, 8). Others, however, were able to obtain good results. In 1895, Meeh quoted by Boyd (2), obtained specific gravities ranging from 1.018 to 1.053 on four dead infants. In a subsequent experiment (2) on ten living persons from 12 to 60 years old, he obtained a range of specific gravities from .946 on deepest inspiration to 1.071 on deepest expiration.

Ziegelroth, as cited by Boyd (2), reported similar values as did Meeh for 22 adult men. The subjects were immersed only up to the head, the volume of it being found from other measurements. The specific gravities during deepest expiration ranged from 1.013 to 1.069.

In 1932, Zook (19) determined the specific gravities of an unselected group of boys ranging in age from 5 to 19 years. The values obtained for deepest inspiration ranged from .978 to 1.000 and for deepest expiration from 1.021 to 1.080. In 1902, Wengler (2) obtained the specific gravity of 3 men and 3 women, who were allowed to breathe through a mouthpiece while submerged. The values thus obtained ranged from 1.013 to 1.042, the range being slightly narrower than that obtained by the other workers. These figures are still in accordance with those showing a greater range, because Wengler's determinations were made during quiet breathing. The others were made on deepest inspiration and deepest expiration.

The results of the preceeding experiments show rather conclusively that the amount of air in the lungs has a profound influence on body specific gravity. This is evidenced by the lower values obtained on inspiration and higher values at expiration.

However, the failure of other workers to show this trend may have been due to imperfections of their apparatus like some of those previously mentioned. Some workers attempted to overcome this by employing a method known as hydrostatic or underwater weighing to find specific gravity. This method ascertains body volume simply by weighing the subject under water. Since a submerged body loses weight equal to that of the volume of water it displaces, the volume of the body is then equal to its loss in weight under water. Specific gravity is calculated by the equation:

$$\text{Specific Gravity} = \frac{\text{Wt. in air}}{\text{Wt. in air} - \text{Wt. in water}}$$

This method is superior to the previous one because it eliminates any error in measuring the displaced water. Furthermore, weights can be obtained rapidly and accurately. However, this method does not eliminate the error caused by varying densities and temperatures of the submerging medium. Furthermore, this procedure does not eliminate errors due to failure to correct for the air in the lungs.

Perhaps the first one to employ such a method was Mies in 1899 (2). He used 74 boys and men ranging in age from 8 to 61 years and allowed them to breathe normally through a mask while submerged. Included in his values for specific gravity of these subjects were those of 28 adult prisoners determined by water displacement. The values thus obtained ranged from 1.012 to 1.082. No conclusions were drawn as to a comparison of the two methods.

Sytcheff (2), however, decided that underwater weighing was best and used this method on 103 child cadavers ranging in age from birth to 15 years. Their specific gravities ranged from 1.000 to 1.057. Griffith (2) used 38 stillborn fetuses and obtained a range of specific gravities from 1.032 to 1.060 for those 2 months and 9 months from the time of conception, respectively.

In 1927, Mumford (2) determined the specific gravities of 80 boys ranging in age from 13 to 18 years. Underwater weights were taken at various stages of respiration. The results showed mean specific gravity values of 0.975 to 0.982 for deep inspiration, 1.045 to 1.065 for deep expiration, and 1.011 to 1.019 for mid respiration. By analyzing the results of Sytcheff and Griffith, it can be seen that the onset of breathing at birth decreases body specific gravity. These results as well as those of Mumford are further evidence that the amount of air in the lungs influences the specific gravity of the human body.

From all the results mentioned above, no conclusions can be drawn as to the actual specific gravity of the air-free body. Obviously, the results obtained at deepest expiration most nearly approach this, but a volume of air remains in the lungs and intrapulmonic spaces even after deepest expiration. This volume, known as residual air volume, cannot be included as part of the body volume when specific gravity is to be determined. The residual air volume amounts to about 1,400 cc. in the adult male (1, 18), and is too large to be disregarded, as this amount of air will still cause considerable buoyancy of a submerged subject.

The initial work on the specific gravity of the air free human body was performed in 1942 by Behnke et al. (1). He used 99 healthy navy men, whose ages ranged from 20 to 40 years. Their residual air volume was first determined by the method of helium substitution (18), and body volume was subsequently determined by underwater weighing. The air-free body specific gravities thus obtained ranged from 1.021 to 1.097. To illustrate how the residual volume correction is applied, assume this volume to be 1.20 liters and take an underwater weight at full expiration of 4.30 kilograms. Using water as density 1.00, a residual volume of 1.20 liters buoys a subject to the extent that his underwater weight is decreased by 1.2 kilograms. Therefore, the exclusion of this volume will increase his underwater weight by 1.20 kilograms and his air free weight will be 4.30 + 1.20 or 5.50 kilograms. This final weight is then used to obtain the specifid gravity of the air free body.

Behnke states that for a group of 20 or more men, an average value of 1,450 cc. for residual volume can be used without causing an error greater than 0.003 in specific gravity. However, in a subsequent experiment Welham and Behnke (16) found that trained athletes have a higher residual volume than navy men. With the above technique, Behnke was able to relate specific gravity with the total fat content of the body. Knowing that all body components except adipose tissue have a specific gravity greater than 1, Behnke concluded that his low values were associated with high fat content and the high values with low fat content. Welham and Behnke (16) subsequently made a study of specific gravity as related to fat content of 75 navy men. They grouped the values thus obtained into high (those above 1.074), low (those below 1.060) and middle (those between 1.060 - 1.074). They also tentatively picked the value 1.060 as a dividing line for obesity.

According to these results, one would expect an increase in body specific gravity as the amount of fat decreased. With this in mind, Brozek (3) followed the change in specific gravity of 34 men, of average age 25.4 years, under conditions of semistarvation. Their initial specific gravities averaged 1.071 and after 24 weeks of starvation, they increased to 1.089 with a mid period value of 1.084. Brozek used the same procedure as Behnke and corrected all body volumes for a residual capacity of 1,450 cc. He considered this technique reliable.

In 1950 Osserman _et al._ (9) used this same technique to find the specific gravities of a group of normal men. The values obtained ranged from 1.022 to 1.100 with an average of 1.068. These results agree very favorably with those of Behnke (1), Welham (16), and Boyd (2). At the present time this technique, as developed by Behnke, is regarded as the standard method of determining the specific gravity of humans. By employing this method, various workers (4, 5, 6, 11) have shown that body specific gravity does not remain constant, but will vary inversely with the amount of adipose tissue in the body.

Air displacement. - The above discussion is a review of the more significant work performed on human specific gravity as determined via water displacement. As previously mentioned, this method depends upon an accurate measurement of the air-free body volume. One way of determining this is to measure the amount of water it displaces, hence the name, "water displacement". Similarly, since a body displaces a volume of water which is equal to its own volume, it must also displace the same amount of air.

This principle was applied some 80 years ago when Jaeger, quoted by Liuzzo (7), attempted to measure body volume in a Kopp volumeter. His technique consisted of changing the volume of an airtight chamber by a known amount, and then finding the volume of air within from the resultant pressure changes. However, he was aware that complications would arise when living subjects were used, because their gasous exchanges would alter the resultant pressure differentials.

About 1916, Pfaundler (7) constructed an airtight cylindrical chamber (25 x 55 cm) in which a child cadaver was enclosed. The pressure within was then changed by known amounts and the volume determined from pressure-volume relationships. He allowed the temperature between the cadaver and the air to come to a complete equilibrium, before making the pressure readings. Consequently, about 1½ hours were required to obtain one volume reading. This technique was deemed too time consuming to be acceptable and definitely inapplicable to living subjects. Pfaundler also determined the specific gravities of these cadavers by water displacement and compared the results. They proved quite variable as water specific gravity averaged 0.9875 while air displacement gave an average specific gravity of 1.143.

Pfleiderer (7) determined the specific gravity of live humans by introducing a positive pressure into a chamber containing the subject. The resultant pressure was compared with that obtained when the same amount of air was introduced into the empty chamber. The volume was determined from the difference between these 2 resultant pressures. This method required less time than Pfaundler's, but it was still not considered satisfactory to minimize subject discomfort. Pfleiderer also recognized and experienced difficulties from pressure fluctuations caused by gasous exchanges of the living subject.

In 1929 Kohlrausch (7) used air displacement to find the specific gravity of 4 dogs. His method was similar to that used by previous workers. A known volume of air was introduced into an airtight chamber containing the animal, and its body volume was ascertained from the resultant pressure changes. The values for specific gravity ranged from 1.046 to 1.074. In a subsequent paper, Kohlrausch (7) reported that one of these dogs showed an increase in specific gravity from 1.054 to 1.074 after a one month workout on a treadmill.

Bohnenkamp (7) reported on his using a modified air displacement technique to find the specific gravity of humans. This method consisted of introducing a known amount of oxygen into a chamber. Body volume was then found from the pressure differences that resulted with and without the subject therein. After making corrections for the gasous exchanges that occurred, he found average specific gravities of 1.095 for males and 1.070 for females. The whole group showed an extreme range from 0.980 to 1.130.

Another modification of the air displacement method is the introduction of a known amount of helium into an airtight chamber containing the subject. The helium concentration is subsequently determined and body volume ascertained from a volume concentration relationship in the following way:

$$\text{Vol. of Animal} = \text{Volume of empty chamber} - \frac{\text{Volume of added gas}}{\text{Final concentration of added gas}}$$

Walser <u>et</u> <u>al</u>. (15) used this technique quite successfully on cats and obtained a live specific gravity which differed from that of the lung-free carcass by an average of .013. In 1955, Siri (13) designed a complex apparatus for finding human body volume which employed the helium dilution principle. It was a closed circuit system consisting of 2 chambers. With the subject in one and a known amount of helium in the other, the gasses of the system were mixed. The resultant helium concentration was determined by thermal conductivity, and was then related to body volume. Siri was able to determine body volume with an estimated standard deviation of $\pm .12$ liters. He used 37 men and women of weights ranging from 55 to 97 kilograms and obtained a range of specific gravities from .990 to 1.076.

Perhaps the most recent work on air displacement specific gravity was performed by Liuzzo et al. (7) of which the project reported herein is a continuation. He employed the use of negative pressures to ascertain the body volume of guinea pigs. His apparatus consisted of 2 chambers of known volume which were connected to each other, to a mercury U tube manometer, and to a saturator bottle. The animal was enclosed in one chamber, while a known negative pressure was drawn on the other (P_1). The pressure was allowed to equalize between the 2 chambers and the resultant amount again recorded (P_2). The volume of the occupied chamber was calculated with the equation:

$$V_3 = \frac{P_1 - P_2}{P_2} \left(V_1 \frac{273}{273 + T}\right)$$

V_3 = volume of occupied animal chamber.

V_1 = known volume of evacuation chamber.

V_2 = volume of empty animal chamber as determined by following the above procedure with an empty chamber.

P_1 = pressure reading before equalization.

P_2 = pressure reading after equalization.

T = temperature change in evacuation chamber.

Body volume was found by subtracting V_3 from V_2.

It can be seen from the equation that the volumes were corrected only for temperature changes in the evacuation chamber. The need for a vapor pressure correction was eliminated by keeping both chambers saturated during the course of operation. The results for live specific gravity of these guinea pigs ranged from 1.0632 to 1.1918. The specific gravity of their eviscerated carcasses ranged from 1.0261 to 1.0926. These results show a correlation of .742. Liuzzo also correlated live specific gravity with carcass fat, water, protein, and ash at two levels of negative pressure. At a partial vacuum of 320 mm. Hg., the correlation coefficients were -.70, 0.67, 0.68 and 0.58, respectively. At a partial vacuum of 120 mm. Hg., the corresponding values were -.82, 0.81, 0.72 and 0.72, respectively.

These results were deemed good enough to warrant the application of this technique to the resolution of body composition of larger animals. The study reported herein is an approach to this problem. Humans were chosen for this study in order that their specific gravities obtained by air displacement could be compared with those by water displacement.

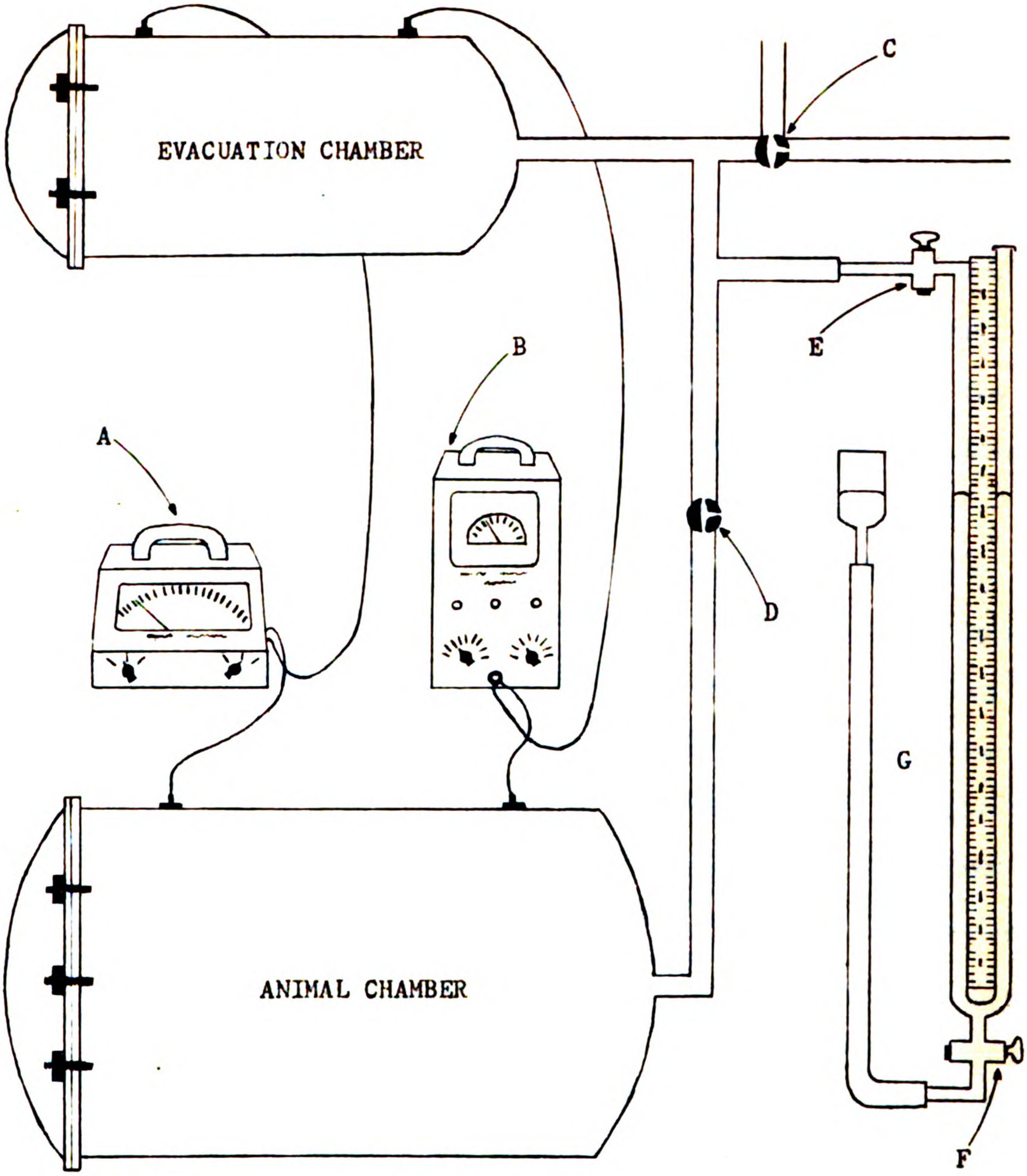
EXPERIMENTAL PROCEDURE

Human Subjects

The subjects used were adult male human beings who volunteered for the study. The weight of each subject in air was taken on a Toledo platform scale, which was read accurately to the nearest one-fourth pound. Since the objective was to compare the results of two methods of measuring specific gravity, measurement by underwater weighing was made immediately before or after that by air displacement. Consequently, the subjects were not required to fast for any length of time prior to the measurements. In order to minimize errors due to differences in wearing apparel, each subject wore only swimming trunks for both measurements.

Measurement of Body Volume by Air Displacement

The principle used to determine body volume in this study was the same as that reported by Liuzzo *et al.* (7). The basic design of the apparatus was also similar to that used by Liuzzo (7), differing primarily in the size of the chambers. A diagram of the apparatus is shown in Figure I. The animal chamber had a capacity of approximately 460 liters, and the evacuation chamber 178.6 liters. Both chambers were sealed by bolting their doors against a rubber gasket. A suitable arrangement of pipe fittings and stopcocks served to control the flow of air to and from the chambers in any combination desired.



A- HYGROMETER
B- THERMISTOR
C&D- 3-WAY VALVES
E&F- GLASS STOPCOCKS
G- U TUBE MERCURY MANOMETER AND RESERVOIR

Figure I. Diagrammatic drawing of the apparatus designed to measure body volume by air displacement.

The details of the procedure for measuring the volume of the occupied and empty animal chamber were similar to those outlined by Liuzzo (7). However, several modifications were found to improve the technique as evidenced by the results obtained. The constant volume manometric technique was not employed, since replicate measurements were made more rapidly and more precisely without its use. Likewise, greater precision was obtained by keeping the air in the evacuation chamber as dry as possible. This was accomplished by installing calcium chloride desiccators in the intake line so that the air was dried before entering the chamber. A desiccator was also placed inside the evacuation chamber. Since the hygrometer, used to observe relative humidity, was sensitive only for values greater than 78%, the relative humidity of the air in the animal chamber was maintained above this level. From values of relative humidity and temperature, a value for vapor pressure of water was computed and incorporated into the equation for calculating chamber volumes. This value served to correct for the amount of water vapor expired by the subjects while inside the chamber.

Temperatures and pressures were observed with a thermistor and a U-tube mercury manometer, respectively. Relative humidity and temperature were recorded concurrently with each pressure reading. The volume of the animal chamber was calculated with the following equation:

$$V_2 = V_1 \frac{\frac{P^1{}_s}{T^1{}_s} - \frac{P^0{}_s}{T^0{}_s}}{\frac{BP - VP^0{}_L}{T^0{}_L} - \frac{P^1{}_L - VP^1{}_L}{T^1{}_L}}$$

V_1 = known volume of the evacuation chamber.

V_2 = volume of the empty animal chamber.

$T^o{}_s$ = temperature of evacuation chamber before equalization.

$T^1{}_s$ = temperature of evacuation chamber after equalization.

$T^o{}_L$ = temperature of animal chamber before equalization.

$T^1{}_L$ = temperature of animal chamber after equalization.

$P^o{}_s$ = pressure of evacuation chamber before equalization.

$P^1{}_s$ = pressure of evacuation chamber after equalization.

$P^1{}_L$ = pressure of animal chamber after equalization.

BP = pressure of animal chamber before equalization, or barometric pressure.

$VP^o{}_L$ = vapor pressure of water, at temperature $T^o{}_L$, in the animal chamber before equalization.

$VP^1{}_L$ = vapor pressure of water, at temperature $T^1{}_L$, in the animal chamber after equalization.

All the pressure values were expressed in units of absolute millimeters of mercury and those for temperature in degrees Kelvin.

Each subject was placed in the animal chamber and four successive volume measurements were made. The resulting values were averaged, designated as V_3, and incorporated into the following formula, which then gave a figure for body volume.

$$\text{Body Volume} = V_2 - V_3$$

The specific gravity of each subject was calculated by dividing his weight in air by his body volume.

Measurement of Body Volume by Underwater Weighing

The volume of each subject in this study was also determined by an underwater weighing technique similar in principle to that used by Behnke *et al.* (1). A photograph of the apparatus used for underwater weighing is shown in Figure II. The chair was suspended from a load cell which in turn was attached to a block. The whole assembly was raised and lowered with a winch. The device for recording weight in this study differed from Behnke's (1) in the following respect. It consisted of a Sanborn Twin-Viso Recorder, Model 60-1300, complete with a Strain Gauge amplifier, Model 64-500-B. The Strain Gauge pick-up was a SR-4 load cell. This instrument automatically and continuously recorded the weight of any object attached to the load cell. Before any values were recorded and used for volume measurements, the instrument was balanced and calibrated with standard weights according to the directions supplied by the manufacturer.

The underwater weighing was performed in a swimming pool when the temperature of the water was held at approximately 80°F. The subjects were fastened into the chair, fitted with the mouthpiece of the device for breathing underwater, and submerged to a fixed depth. The subjects were previously instructed to make a complete expiration while submerged. The net underwater weight of the subject was taken as the weight of the chair and subject, minus that of the empty chair, which was weighed at the same depth as the subject. The net weight was adjusted by adding to it the weight of a volume of water equal to the residual air lung volume of the subject.

Figure II. Apparatus used to measure body volume

by underwater weighing.

Behnke (1) stated that a residual air volume of 1.450 liters can be used as an average value for each individual when groups of 20 or more men are used. An error of ± 200 cc. in estimating residual volume will cause an error of less than ± 0.003 in specific gravity. The adjusted net body weight of each subject was then incorporated into the following formula to find body volume.

$$\text{Body Volume} = \text{Weight in air} - \text{Weight in water}$$

Specific gravity was calculated by dividing weight by volume.

RESULTS AND DISCUSSION

The values for weight, volume, and specific gravity of each subject are shown in table 1. The specific gravities obtained by air displacement ranged from 1.045 to 1.167 with an average value of 1.102; whereas, those by water displacement ranged from 1.034 to 1.097 with an average value of 1.062. The correlation between the specific gravities obtained by the two methods is shown in Figure 3. The regression line for the dependence of water specific gravity on air specific gravity, Y on X, is ($Y = 0.844 + 0.197X$). The regression equation for X on Y is ($X = 0.388 + 0.672Y$). The regression coefficient (b) of Y on X is 0.197 ± 0.103 and b_{XY} is 0.672 ± 0.350. The correlation coefficient, which is the geometric mean of the regression coefficients, is 0.364. None of the above coefficients are significant. The correlation coefficient shows the two-way average of relationship between the two sets of values since one set is not dependent on the other.

Specific gravity determined by air displacement showed more variation than similar values determined by underwater weighing. The degree of variation within the values by air displacement was significantly greater than the degree of variation within the values by water displacement. Thus, it appears probable that the greatest errors in measuring body volume occurred in the air displacement method. However, it should be pointed out that neither method was validated by a more accurate procedure, and thus a reliable means of

TABLE 1. DATA FOR AIR AND WATER SPECIFIC GRAVITY

Subject	Kg. Weight	Volume Air	Volume Water	Specific Gravity Air	Specific Gravity Water
1	80.15	68.88	74.05	1.1636	1.0824
2	68.22	58.46	63.57	1.1670	1.0731
3	56.81	50.59	54.97	1.1229	1.0335
4	61.17	52.68	55.77	1.1612	1.0968
5	58.97	52.66	56.92	1.1198	1.0360
6	74.16	66.07	70.82	1.1224	1.0472
7	64.32	57.82	59.03	1.1124	1.0896
8	66.23	59.89	61.19	1.1059	1.0824
9	76.21	68.49	71.04	1.1127	1.0728
10	78.70	69.34	73.02	1.1350	1.0778
11	75.52	68.60	71.36	1.1009	1.0583
12	92.53	83.26	86.30	1.1113	1.0722
13	73.67	66.65	70.33	1.1053	1.0475
14	70.54	64.97	66.02	1.0857	1.0685
15	72.35	65.72	66.22	1.1009	1.0926
16	84.60	78.19	79.93	1.0820	1.0584
17	81.56	75.35	77.20	1.0824	1.0565
18	76.61	70.52	72.47	1.0864	1.0571
19	69.06	63.80	65.53	1.0824	1.0539
20	94.17	89.57	90.45	1.0514	1.0411
21	73.94	68.42	69.93	1.0807	1.0574
22	92.72	81.32	89.25	1.1402	1.0389
23	78.25	73.34	74.38	1.0669	1.0520
24	82.78	78.92	79.18	1.0489	1.0455
25	97.30	92.45	94.02	1.0525	1.0349
26	66.54	63.66	61.70	1.0452	1.0784
		Average		1.1018	1.0617
		Standard Deviation		± 0.0346	± 0.0188

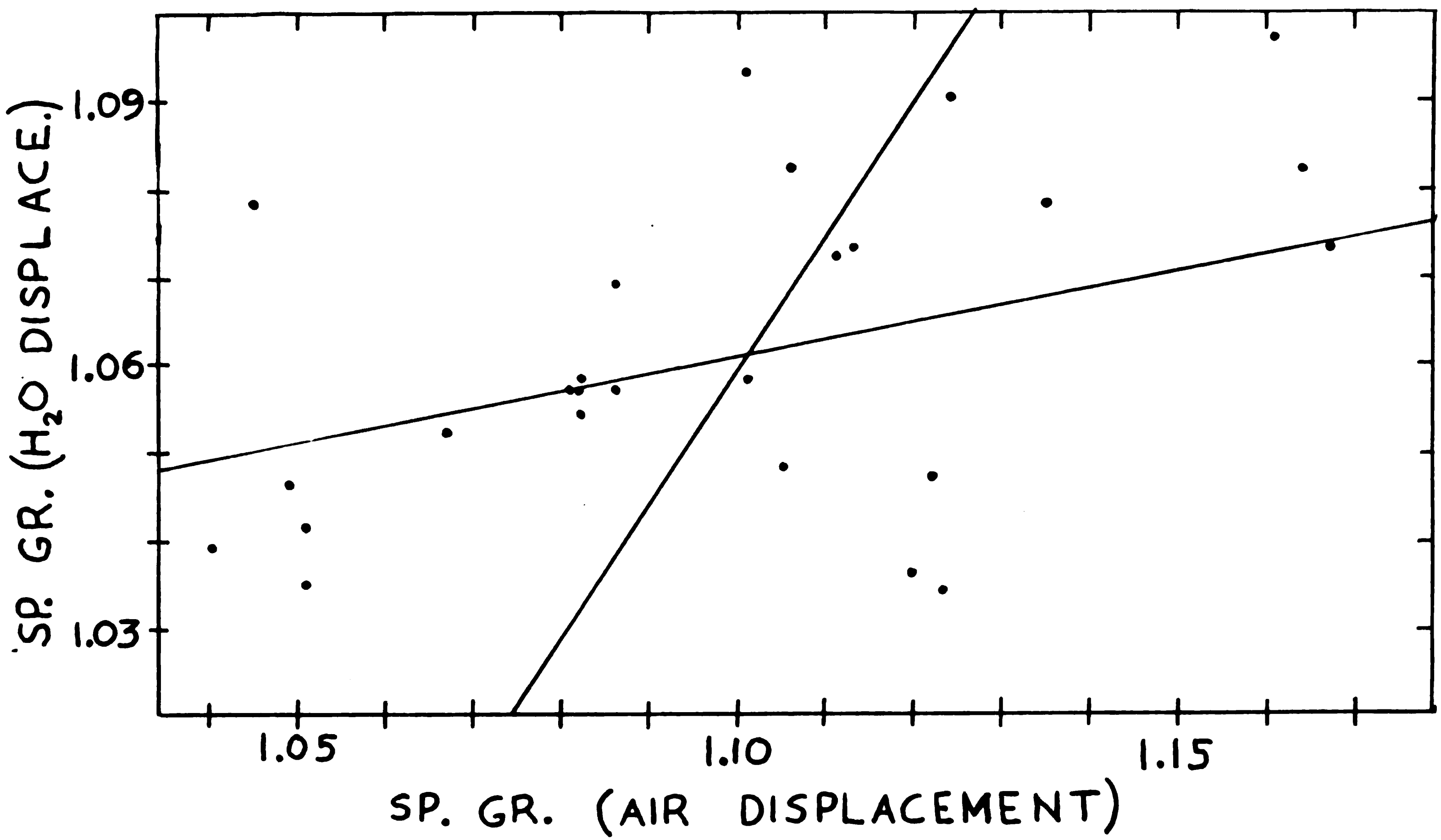


Figure 3. Regression lines of air and water specific gravity.

assessing accuracy was not available. With the exception of one value, each specific gravity measurement obtained by air displacement was higher than its corresponding value in water. All values were included in the above analysis; however, when the values for subject number 26 were excluded from analysis, the correlation coefficient was significant at the 5% level.

A major source of error in computing volumes appeared to be due to variation in the relative humidity of the air inside the animal chamber. When the volume of the air in the animal chamber was computed without including a correction for vapor pressure, a correlation coefficient of -0.50 was obtained between volume and relative humidity. However, when a correction was applied for vapor pressure, the correlation coefficient was -0.26. Although the correlation coefficient was not statistically significant after applying the correction for humidity, the low negative relationship indicated that the correction did not completely remove the effects of relative humidity on volume. Calculations showed that if a representative value for relative humidity were in error by as little as 1%, the computed volume of an average subject would vary by approximately 0.850 liters which would change the specific gravity by 0.016 units.

The pressure in the chambers was recorded with a mercury manometer, which was read to the nearest 0.1 millimeter. If a representative pressure value were in error by as much as 0.1 millimeter, the magnitude of the volume error would depend on which reading was in error. If the error was made in the pressure reading of the small chamber before equalization, the computed volume of an average subject would vary by 0.140 liters, which would change the specific gravity by 0.002. However, if the error was made after equalization, when the pressure in both chambers is equal, the volume would vary by 0.50 liters, which will alter the specific gravity by 0.008. Such errors could not be corrected for since the direction or magnitude or even the existence of such mistakes could not be ascertained in this study. Since such errors were inherent in the apparatus, it is assumed that they could have occurred. Due to the formation of oxide in the mercury and on the inside surface of the manometer, errors of 0.50 millimeters would not seem to be uncommon in making pressure readings. Errors of this magnitude would alter the volume of an average subject by approximately 2.40 liters which would change the specific gravity by 0.041. If an error of this magnitude were made in reading the pressure of the evacuation chamber before equalization, the change in specific gravity would only be 0.012.

Another major source of error could arise from the inability of the operator to obtain a representative temperature reading in the animal chamber. Temperature was read with a thermistor to the nearest 0.1°C. An error of 0.1° in temperature, would change the body volume of an average subject by 0.440 liters, and the specific gravity by 0.004. It was also observed that the temperature of the air within the animal chamber was not always uniform throughout. The temperature of the air next to the subject's body would be expected to differ from that at the surface of the chamber, especially if room temperature was markedly different from body temperature. The small electric fan, which constantly mixed the air within the chamber, did not circulate the air fast enough to minimize this differential. If a representative temperature of the animal chamber were in error by as little as 0.5°, at constant relative humidity, the computed volume would vary by approximately 5.40 liters and the error in specific gravity would be 0.079.

The average subject referred to in the above discussion had a specific gravity of 1.0934 and a volume of 69.70 liters. This volume was 0.15 times the volume of the empty chamber. If this proportion were increased by increasing the volume of the above subject at constant specific gravity, the magnitude of the errors cited above would decrease as shown below.

Volume	$\frac{\text{Vol. subject}}{\text{Vol. chamber}}$	Error	△ Volume	△ Sp. Gr.
69.70	0.15	0.5 mm.	2.4 l.	0.040
		0.5°C.	5.4 l.	0.079
200.34	0.44	0.5 mm.	1.4 l.	0.008
		0.5°C.	2.71 l.	0.015
262.99	0.58	0.5 mm.	1.09 l.	0.005
		0.5°C.	1.71 l.	0.007
325.44	0.71	0.5 mm.	0.74 l.	0.003
		0.5°C.	0.93 l.	0.003

As the proportion increases, the resultant errors in calculating volume and specific gravity decrease. The above figures indicate that the animal should occupy at least one half the volume of the chamber for reliable accuracy.

The technique used in this study to record the underwater weight of the subjects, was not as accurate as a direct reading gram scale. The grid paper on which weight was recorded, was read accurately to the nearest 0.10 millimeter. This reading in terms of weight amounted to 0.065 kilograms. However, an error of this magnitude in weight would change the specific gravity by only 0.001. Assuming an error of 0.50 millimeters was made due to mechanical variation, the computed volume of an average subject would be changed by 0.32 liters, and specific gravity would vary by 0.005. The subjects used in this study were given no previous training at expelling all the air from their lungs; consequently, this could have become a source of error. If a subject expelled only one-half of his expiratory reserve volume, his computed body volume would increase by approximately 0.50 liters, and specific gravity would decrease by 0.010.

The results indicated that factors other than those mentioned above were responsible for the low water specific gravities for subjects three, five and six. These individuals appeared to be very lean. These errors could have been made if the weight of the empty chair was not taken at the same depth as the subject. Furthermore, if one of the many control dials on the Sanborn Recorder were accidentally moved, the resultant values for weight would also be in error.

SUMMARY

The specific gravity of 26 adult male human beings was determined by two methods of measuring body volume. For the air displacement method, the subject was placed in a steel chamber of known volume and subjected to a known reduction in pressure. Volume was then computed from the pressure-volume relationship. For the underwater weighing method, the subject was submerged in a swimming pool and his weight was recorded with a Sanborn Recorder connected to a weight sensitive load cell and a Strain Gauge amplifier.

The correlation coefficient for the specific gravity values obtained by the two methods was not statistically significant; although, there was a positive relationship. The values determined by air displacement showed more variation than those by water displacement. The potential errors with the air displacement method appeared to be of greater magnitude than those for the water displacement method.

LITERATURE CITED

1. Behnke, A. R. Jr., B. G. Feen, W. C. Welham. 1942. The specific gravity of healthy men. J. Amer. Med. Assoc. 118:495.

2. Boyd, E. 1933. The specific gravity of the human body. Human Biol. 5:646.

3. Brozek, J. 1946. Changes in specific gravity and body fat of young men under conditions of experimental semi-starvation. Fed. Proc. 5:13.

4. Da Costa, E. and R. Clayton. 1950. Studies of dietary restriction and rehabilitation. II. Interrelationships among the fat, water content and specific gravity of the total carcass of the albino rat. J. Nutr. 41:597.

5. Dupertuis, C. W., C. Pitts, E. F. Osserman, W. C. Welham and A. R. Behnke, Jr. 1951. Relation of specific gravity to body build in a group of healthy men. J. Applied Physiol. 3:676.

6. Kraybill, H. F., H. L. Bitter and O. G. Hankins. 1952. Body composition of cattle. II. Determination of fat and water content from measurement of body specific gravity. J. Applied Physiol. 4:575.

7. Liuzzo, J. A., E. P. Reineke and A. M. Pearson. 1958. An air displacement method for determining specific gravity. J. An. Sci. 17:513.

8. Murlin, J., B. R. Hoobler. 1913. The energy metabolism of normal and Marasmic children with special reference to the specific gravity of the child's body. Proc. Soc. Exper. Biol. Med. 11:115.

9. Osserman, E. F., G. C. Pitts, W. C. Welham and A. R. Behnke, Jr. 1950. In vivo measurement of body fat and body water in a group of normal men. J. Applied Physiol. 2:633.

10. Pitts, G. C. 1956. Body fat accumulation in the guinea pig. Amer. J. Physiol. 185:41.

11. Rathbun, E. N., and N. Pace. 1945. Studies on body composition. I. The determination of total body fat by means of the body specific gravity. J. Biol. Chem. 158:667.

12. Robertson, J. 1757. An essay towards ascertaining the specific gravity of living men. Phil. Trans. Roy. Soc. London. Vol. 50:71 or 30.

13. Siri, W. E. 1955. Apparatus for measuring human body volume. Rev. Sci. Instr. 27(9):729.

14. Spivak, C. D. 1915. The specific gravity of the human body. Archiv. Int. Med. 15:628.

15. Walser, M. and S. N. Stein. 1953. Determination of specific gravity of intact animals by helium: comparison with water displacement. Proc. Soc. Expt. Biol. Med. 82:774.

16. Welham, W. C. and A. R. Behnke, Jr. 1942. The specific gravity of healthy men. J. Amer. Med. Assoc. 118:498.

17. Whiteman, J., J. A. Whatley and J. C. Hillier. 1953. A further investigation of specific gravity as a measure of pork carcass value. J. Ani. Sci. 12:859.

18. Willmon, T. L., A. R. Behnke, Jr. 1948. Residual lung volume determinations by the methods of helium substitution and volume expansion. Am. J. Physiol. 153:138.

19. Zook, D. E. 1932. The physical growth of boys: a study by means of water displacement. Am. J. Diseases Child. 43:1347.