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PHYSIOLOGICAL BASIS OF FLOATING IN WATER

REPORT 256
22 FEB. 1961

UNITED STATES ARMY
MEDICAL RESEARCH AND DEVELOPMENT COMMAND

Report No. 256
Project No. 6X60-11-001, Nutrition
Subproject 5

22 February 1961

PHYSIOLOGICAL BASIS OF FLOATING IN WATER

OBJECT:

To specify the volume of air required to float nude men with their heads out of water and, from this, to indicate the further volume required when loaded with clothing and equipment.

SUMMARY:

Suppose that the full vital capacity is needed to ventilate the lungs during the exertion of crossing a deep body of water. This leaves two components of gross body composition which will "float" and two which will "sink". The two which float are the residual lung volume and the body fat; the two which sink are bone mineral and body protein. Among men of diverse body weights, the above components occur in proportions such that it can be shown that the lean 90 kg man needs more air for bouyancy than heavier or lighter men. In order to float with at least his head out of water, he needs almost 11.6 liters of air when nude. In what follows, the human body dimensions pertinent to the problem are treated so as to make it easy to consider the mass: volume relationships of clothing and equipment, with the view in mind of insuring that a man loaded with equipment is enabled to float.

APPROVED:

Marion E. McDowell

MARION E. McDOWELL
Lt. Colonel, MC
Commanding Officer

INTRODUCTION

Often it is asked how best to float a man. To answer this requires, first of all, a consideration of relationships involving mass and volume of the human body. These dimensions can be measured with a balance and a volumeter (1). The following example illustrates the problem. An 82.6 kg man with fully inflated lungs had a volume of 84.4 liters. In this "full" respiratory position his density was 0.979 kg/liter. After he had forcefully emptied his lungs, his body volume decreased to 78.8 liters. While in this "empty" respiratory position, his density was 1.049 kg/liter, the difference between 84.4 and 78.8 liters being called the vital capacity of the lungs (2). Even after blowing out his vital capacity, his lungs contained a residual volume of air which amounted to 1.4 liters. Thus, the volume of the total hard and soft tissues, provided gas was absent in the bowels, was 77.4 liters. The quantity of body fat (F) can be computed (3) from the body weight (M) and the total tissue volume (V) in accordance with $F = 4.834\ V - 4.366\ M$. This man, therefore, had close to 11.8 kg of fat, giving him a fat-to-body-weight proportion, F/M, of 0.143 kg/kg which is typical of that in young men (1). Individual variations in the above lung volumes, together with the various proportions of body fat in a group of 107 presumably healthy men from 17 to 67 years of age, account for the wide range in fat and density shown in Figure 1. One man had such a small fat burden that even with totally filled lungs, his density was greater than unity. Accordingly, he would sink in fresh water of density 1.000, but float in sea water of density greater than 1.007. If this group of men were to blow out their vital capacities, there would remain only six men who would float in fresh water, and these men would have fat proportions in excess of 0.37 kg/kg. Even in sea water with a high density (4) of 1.04, twenty-two men would sink if bouyed only by their residual lung volumes, representing a casualty rate of 44 per cent among the men of less than 30 years of age in the group of 107 men (Appendix I).

It is obvious that individuals engaged in stream crossings can suffer exceedingly high casualty rates. What can be done to make it safe and easy to cross a deep body of water immediately upon arrival? Supposedly, the only way to do this is to supply air in a bladder with a volume sufficient to overcome the excess of mass to volume of the human body, its clothing and necessary equipment. In order to discuss the complete problem, it is necessary to show to what extent the volume should exceed the mass in order to float the leanest nude men with their heads out of water who, to provide ventilation, have completely emptied their lungs of the vital capacity. It is easy then to measure items of clothing and equipment and to equate these in terms of bouyancy required to counteract various combinations of loads. This requires precise definitions, handled mathematically and based on actual measurements of mass and volume in large numbers of men.

DEFINITIONS

V_{max} = maximum volume of the body achieved by fully inflating the lungs .... [liter]

V_{min} = minimum volume of the body achieved by blowing out the vital capacity, V_c, ... [liter]

V_r = residual lung volume .... [liter]

V = total volume of body tissues, provided gas is absent in the bowels .... [liter]

V_f = total volume of ether extractable human body fat which has a density, [d_f = 0.901 (ref 5)] ....[liter]

V_l = total volume of the lean body consisting of the sum of the volumes of water, V_w, bone mineral, V_m, and material rich in protein, V_3, [for which d_w = 0.997, d_m = 2.8, d_3 = 1.40 (ref. 3)] .... [liter]

ϕ = a constant derived from the proportionality occurring among V_w, V_m, and V_3 (see ref 1) .... [0.904 liter/kg]

V_h = the total volume of the head and neck to the level of the first thoracic vertebrum .... [liter]

V_b = the additional volume of air required to float with the head and neck out of water in a medium of known density .... [liter]

M = body weight, measured to nearest 0.1 kg .... [kg]

F = quantity of ether soluble fat estimated from $F = 4.834\ V - 4.366\ M$ .... [kg]

Notations appearing above a quantity or volume symbol: $\wedge$ stands for maximum, and $\vee$ stands for minimum values in a large number of men.

DERIVATION OF THE PROBLEM

The minimum volume which can be achieved by an individual is

$$V_{min} = V_r + V_f + V_l$$

which, due to the fairly uniform proportionality occurring among body water, bone mineral, and body "protein", can be written

$$V_{min} = V_r + \left(\frac{1}{d_f} - \phi \right) F + \phi M$$

From $D = M/V$ relationships the maximum density of an individual with his head and neck out of water to the level of the first thoracic vertebrum is $D_{max} = M/(V_{min} - V_h)$ where V_h is the volume of the head and neck. In order to float, D_{max} must be lowered to the density of the medium. The volume of air required for this is

$$V_b = \frac{M}{D_{medium}} + V_h - V_{min}$$

Although this equation applies to individual men, it is desired to state V_b so as to float all men including those who are extremely lean, of large body weight, with minimum residual lung volume, and with maximum head volume.

In 519 recently measured men (1,6,7-12), including 25 exceptional athletes (13), the minimum quantity of fat increases with body weight and can be described by a hyperbola. The center occurs at 90 kg, 0 kg; the asymptotes have slopes of zero and unity. The hyperbola (Fig 2) states that

$$\check{F} = \left[0.25\ (M - 90)^2 + 77.3\right]^{\frac{1}{2}} + 0.5\ (M - 90) \qquad (1)$$

thus giving $\check{F}$ as a function of M for the 519 men.

In a previous study (6) it was reported that

$$V_r = pM + q\tau - rA + s$$

Taking $\hat{A} = 45$ years of age and $\check{\tau} = \check{F}/k\ (M - \check{F})$ as parameters of $\check{V}_r$, it also is possible to state the minimum residual lung volume as a function of M, thus

$$\check{V}_r = 0.0093\ M + 1.69\ \frac{\check{F}}{M - \check{F}} - 0.21$$

The maximum head volume, measured in a body volumeter (1), can be related to the body weight of 30 men (Appendix I) according to

$$\hat{V}_h = 3.50 + 0.023\ M$$

The final composite statement of the additional volume of air required for flotation in fresh water becomes

$$\hat{V}_b = 0.110\ M - 0.206\ \check{F} - 1.69\ \frac{\check{F}}{M - \check{F}} + 3.71 \qquad (2)$$

where, as in equation 1, $\check{F}$ has been derived as a function of M. Equation 2, when plotted (Fig 3), has a peak value of $\hat{V}_b$ when M = 90 kg. Therefore, it can be concluded that under these physiological conditions 11.6 liters of additional air are required to float all men under 45 years of age, including the leanest.

MILITARY CLOTHING AND EQUIPMENT

Clothing and equipment of a 90 kg soldier were weighed in air and then under tap water at 6^{o} C. after having removed trapped air bubbles by agitation together with exposure to a reduced pressure equal to the vapor pressure of the water. The difference between the above weights is the volume and, from this, the density can be calculated. These dimensions are set forth in Table 1 for a variety of items. In a medium of density = 1, the volume to float an item is equivalent to its weight in water. For example, one pair of boots in item 4 weighed 0.515 kg in water, and, therefore 0.515 liter of air would be required to float these boots.

The above items, when worn and carried, can be arranged in various combinations as in Table 2. The total cumulative load weighs 27.5 Kg in air and has a density of 1.70 kg/liter which, together with the 11.6 liters already taken into account, requires a total of 22.9 liters of air to float a lean 90 kg soldier with his helmet-covered head out of water. Therefore, 23 liters can be accepted as the maximum value of V_b in soldiers of all body weights, when equipped as indicated. Weapons and ammunition account for most of the additional air required.

Obviously, 23 liters of air with its low density could be contained in a light, collapsible container, provided the container was air-tight. Other materials can be compared with such an air container. The densities of some oven-dried woods range from 0.373 for white pine to 0.710 for white oak (14). From these densities, the approximate weight with a bouyancy equivalent to 23 liters of air is obtained by writing the weight in air as a function of the object's density, $M_a = 23D/(1-D)$. Thus, a dry white oak log would need to weigh 56.5 kg or about 124 lb before it would float loaded soldiers. White pine, due to its lower density, need weigh only 30 lbs. However, the probable scarcity of such materials favors the use of a container such as an air mattress into which six full breaths should provide the 23 liters of air.

DISCUSSION

In the course of measuring body volume and weight for the purpose of computing individual burdens of fat, it was realized that a water displacement volumeter (1) could also be used to gather information on a man's chances of floating in water of known density. Although it was found that nearly all men should float when the lungs are fully expanded, it became apparent that only a few should float if the lungs were emptied with a maximum expiration (Fig 1). Moreover, these few men who should always float even in fresh water have unusually large burdens of body fat.

It is possible to visualize the effect of the respiratory cycle as consisting of a period when the lungs are filled, during which time at least part of the head emerges from the water. In the next period when the lungs' tidal volume has been expelled, the head submerges in proportion both to the leanness of the body and the quantity of air expelled. Mr. Fred R. Lanoue, swimming coach in the Georgia Institute of Technology for 25 years, has appreciated the cyclic nature of the buoyancy contributed to the body by the lungs. He teaches the utility of this cycle in his survival method (15).

With the aim in view of stipulating the various extreme conditions which govern flotation among a group of men, we have noted, in accordance with body weight, the occurrence of the least quantity of body fat and the minimum residual lung volume both of which tend for flotation. We have also introduced the maximum volume of the head in proportion to body weight in order to state the maximum volume of air required to float with the head above water at all times even when a maximum expiration has been made. The volume of air thus required is 11.6 liters, and this is needed by lean men of 90 kg nude body weight who are of the type apparently facing the most difficulty in floating; lesser volumes are required for lighter and heavier lean men (Fig 3). The value of V_b for very heavy lean men is somewhat uncertain due to the fact that only 20 out of 519 determinations were on men having body weights in excess of 100 kg. If for the exceptional athlete of M = 118 kg, his value of F = 23 kg is introduced into equation 1, then V_b = 11.5 liters instead of 9.8 liters (Fig 3). According to the present specifications, based on the 90 kg man, even the very large lean man would be supplied with an adequate volume of air for flotation.

It should be noted that in the present selection of extreme conditions it was decided to grant the entire vital capacity for use in ventilation of the lungs, leaving only the residual volume of the lungs for flotation. Measurements performed on United States Navy diving instructors (16) showed similar residual lung volumes of 1.92 and 2.02 liters when standing out of water and in water up to the level of the neck. Although the functional residual capacity was 3.34 liters out of water, this decreased to 2.65 liters in water and exceeded the residual lung volume by only 0.63 liters. Therefore, V_b could be as low as 11.0 liters.

If one considers the effect of immersion in cold water, it is far more likely that the upper value of 11.6 liters should be specified. Carlson and co-workers (17) made a thorough study of body insulation in nine men of diverse body fat burdens when immersed nude on a canvas sling in water which was later cooled to as low as 9° C. His lean men had about one-fourth as much body insulation as the fat men. Moreover, the poorly insulated men, as they cooled, increased their rates of oxygen utilization and respiratory air flow. At times, shivering occurred. In general, it seems that lean men in cold water have increased tidal volumes even when not forced to swim with a load.

From the above consideration of alternatives, in order to insure the safety of all men involved, it seems wise to provide a volume of 11.6 liters for flotation. If clothed, an additional 1.9 liters is required. If clothed and armed, an additional 6.5 liters is needed. This increases until when loaded with 27.5 kg (61 lb) a volume of 22.9 liters is required for flotation when the entire load except the helmet is submerged. It is difficult to state an upper limit for V_b, since loads greater than those indicated can certainly be carried. For those interested in a particular load problem it should be easy to make measurements of the load weight under water and, by accepting the value of 11.6 liters for the lean nude man, to arrive at the volume of air required for flotation by following the methods used in Tables 1 and 2. It should be realized that V_b, as specified, pertains to a volume of air, or its equivalent, which is completely submerged. Although V_b can be stated using the present approach, it must be admitted that the complete solution of flotation in water requires further study of shapes upon which the human body with its loads can be distributed so as to allow for breathing and desirable orientation of the body. Something like a mattress, partly inflated with air, should certainly prove satisfactory. These could be lashed together for group crossings. A durable plastic, air-tight rifle scabbard with cylindrical dimensions of 48 inches in length and 6 inches in diameter would provide for 23 liters of V_b. However, this would be another item of personal equipment, readily lost or abandoned. Although it is concluded, therefore, that much room remains for further military study and testing (18), it is believed that the actual physiological specifications to float the nude body have been derived satisfactorily.

ACKNOWLEDGMENTS

In the course of preparing this report, the authors considered the possible reception of the present conclusions on the part of those who had actually engaged in stream crossings and beach landings. Having inquired for such opinions and experiences, we gratefully acknowledge the suggestions and points of view received from E. M. Baker III, Capt. MSC, once assigned in 1945 to the 27th Infantry Division, and from Thomas Stillwagen, Capt., Inf., presently in patient status at Fitzsimons General Hospital.

LEGENDS

Fig. 1. Showing that among 107 nude men, when the lungs are completely filled, all will float in fresh water ($D_{medium} = 1$) except for one very lean man. However, when the lungs are voluntarily emptied, only seven men will float and these men have large fat burdens.

Fig. 2. Minimum quantity of fat in 519 men of various body weights is defined by the equation for F, excluding 9 out of 25 exceptional athletes (13) denoted by circles. Filled circles denote students, teachers, soldiers, sailors and sedentary men in Formosa, Sweden, and the United States of America.

Fig. 3. The combined influence of minimal body fat and residual lung volume together with maximum head volume requires a maximum volume of 11.6 liters of air for flotation (V_b) when nude body weight (M) is 90 kg.

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TABLE 1. Mass in air (M_a) and in water (M_w) together with density (D) of various items of clothing and equipment.

Item	Number	Description	M_a (kg)	D (kg/l)	M_w (kg)
1a	1	fatigue shirt	0.589	1.54	0.206
1b	1	fatigue trousers	0.528	1.52	0.181
2a	1	undwr (top) - winter	0.403	1.45	0.126
2b	1	undwr (bottom) - winter	0.398	1.46	0.125
2c	1	undwr (top) - summer	0.090	1.50	0.030
2d	1	undwr (bottom) - summer	0.090	1.50	0.030
3	1 pr	wool socks	0.081	1.41	0.023
4	1 pr	leather boots w/laces	1.834	1.39	0.515
5	1	belt w/buckle	0.104	2.75	0.066
6	1 pr	leather gloves w/inserts	0.202	1.33	0.050
7	1	field jacket	1.539	1.62	0.577
8	1	M1 rifle	4.546	1.96	2.172
9	48	rounds ammo	1.234	4.43	0.955
10	3	grenades	2.298	2.73	1.456
11	1	helmet w/liner	1.330	3.79	0.979
12	1	web belt	0.247	2.49	0.148
13	1	poncho	1.300	1.35	0.336
14	1	1st aid packet w/cover	0.105	1.50	0.035
15	1	bayonet w/scabbard	0.720	7.00	0.630
16a	1	empty canteen w/cup & cover	0.537	0.50	-0.530
16b	1	filled canteen w/cup & cover	1.406	1.32	0.339

TABLE 1. (Cont'd)

Item	Number	Description	M_a (kg)	D (kg/l)	M_w (kg)
17	1	mess kit	0.526	6.97	0.452
18	1	pack	1.000	2.00	0.500
19	1	blanket	1.722	1.40	0.522
20	1	shelter half	1.241	1.67	0.500
21	1	shovel & tent pegs & tent poles	1.425	1.62	0.546
22	1	day C-rations	2.499	0.83	-0.524

TABLE 2. Effect of loading with various items (cited in Table 1) on the air required for flotation (V_b).

Remarks	Items	M_a kg	cumul. M_a kg	V_b liter	cumul. V_b liter
Nude body	-	-	-	11.6	11.6
Clothing (winter)	1-7	7.73	7.7	1.93	13.5
Weapon & ammo	8-10	8.08	13.8	4.58	18.1
Helmet (on head)	11	1.33	16.1	1.33	19.4
Web belt accessories	12-16	2.91	19.1	1.49	20.9
Pack & contents	17-22	8.41	27.5	2.00	22.9

APPENDIX I

Listing body volume with filled lungs (V_{max}) and with voluntarily emptied lungs (V_{min}), body weight (M) and fat (F), and age (A) for 107 men recently measured using a body volumeter (1).

A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter	A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter
17	64.0	60.3	63.2	11.5	-	23	79.6	75.4	77.7	17.2	5.11
17	68.8	64.6	68.4	7.2	-	23	84.8	80.2	82.7	18.4	4.79
19	89.3	84.1	86.2	21.2	5.26	24	72.9	69.0	71.1	17.7	4.84
19	101.4	96.5	97.2	31.8	4.54	24	78.4	75.2	78.1	15.0	-
20	50.6	46.7	49.8	5.0	-	24	84.4	78.8	82.6	11.8	-
20	58.7	55.1	55.9	17.8	4.05	24	82.2	76.8	79.3	16.0	-
20	71.9	66.7	70.2	7.6	5.02	24	60.2	57.4	59.4	15.9	-
21	64.6	60.7	63.9	9.9	-	24	72.5	68.5	72.0	11.0	-
21	79.2	73.7	76.6	13.8	5.15	24	78.2	74.2	77.4	13.2	-
21	76.1	71.7	73.7	18.6	4.92	25	86.1	81.8	85.6	12.9	-
22	89.5	84.5	87.8	16.7	5.12	25	70.1	66.1	69.9	8.1	4.26
22	48.1	44.7	47.2	8.4	3.53	25	83.8	78.3	82.4	9.0	-
23	71.1	67.4	71.6	6.9	-	25	70.6	66.6	69.7	15.9	-
23	61.0	57.6	60.9	10.7	-	25	79.2	75.6	77.9	17.3	-
23	74.6	70.5	73.8	12.3	4.96	26	66.6	62.6	65.5	13.6	4.26
23	77.8	73.4	74.7	23.1	4.25	26	69.2	65.4	67.3	16.7	-

APPENDIX I (Cont'd)

A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter	A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter
26	70.0	65.8	69.4	7.5	-	31	94.5	89.4	92.4	17.1	4.67
26	79.4	74.9	77.5	15.3	-	34	98.8	93.3	95.8	22.1	-
27	63.4	60.3	62.4	15.3	-	34	90.6	86.4	87.7	27.3	-
27	80.6	74.2	76.3	17.5	-	34	86.0	82.6	84.4	22.4	-
27	80.4	74.8	76.1	21.3	-	36	84.8	80.6	80.9	30.9	-
27	104.2	101.5	101.0	40.1	-	36	92.2	88.6	90.7	22.1	-
27	84.5	80.5	81.1	28.7	4.90	37	59.4	55.8	57.0	16.8	4.03
28	72.5	68.6	70.9	16.5	5.13	38	101.0	98.5	100.6	24.7	-
28	80.6	77.0	79.3	18.6	-	39	77.6	74.1	76.1	18.3	4.52
28	78.4	73.0	76.4	10.1	-	39	71.6	68.4	69.9	20.8	4.45
29	121.6	116.5	117.7	36.2	-	39	71.4	67.8	69.5	17.4	-
29	76.3	70.2	73.2	12.3	-	39	73.6	69.7	72.4	13.7	-
30	79.9	75.2	77.5	17.0	-	39	69.9	66.6	69.2	14.4	-
30	67.3	62.6	64.1	18.4	-	39	77.4	73.0	74.5	20.9	-
31	69.2	65.9	56.8	22.0	-	40	71.7	68.2	69.5	22.1	-
31	87.6	83.0	86.2	15.1	-	40	83.4	79.3	81.0	21.3	-
31	89.2	85.6	88.0	21.8	-	41	61.8	57.9	61.0	9.8	-

APPENDIX I (Cont'd)

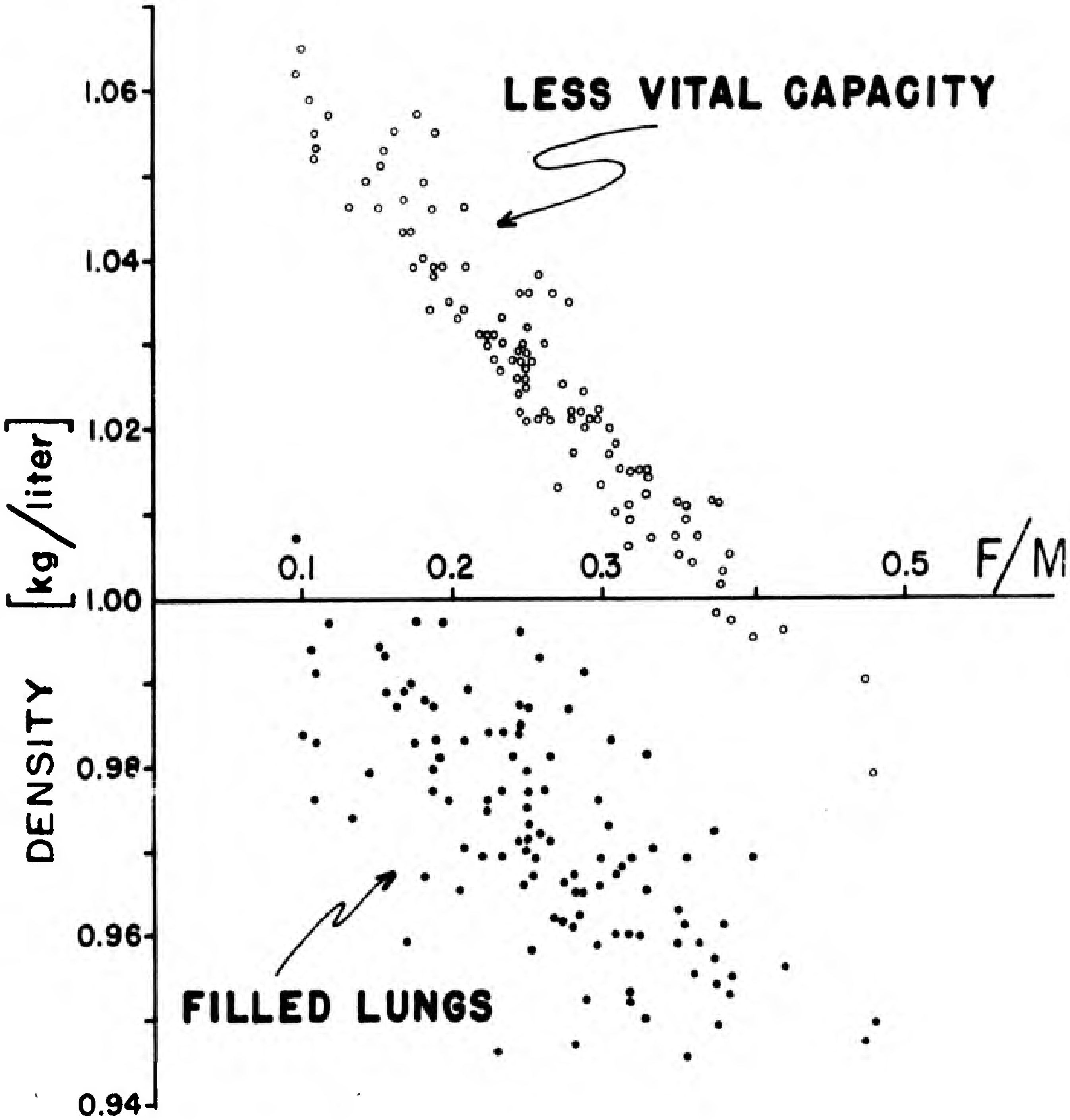
A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter
41	79.6	75.2	77.3	19.1	4.60
41	63.9	59.7	60.4	21.3	-
41	79.0	75.3	75.8	27.4	-
42	88.6	84.9	84.6	32.4	-
42	74.7	70.7	71.7	23.3	-
42	68.8	65.8	68.0	17.0	-
43	82.2	78.6	80.3	20.1	-
43	66.8	[illegible].6	65.4	16.2	-
43	86.1	81.3	83.1	23.3	-
44	83.9	81.1	82.2	26.9	4.92
45	71.5	67.8	69.8	18.2	-
45	59.8	55.5	57.5	15.3	-
45	59.1	55.9	57.1	17.0	3.88
46	99.7	96.0	96.7	32.0	-
46	104.3	99.5	100.1	31.8	5.49
46	96.2	91.7	93.6	24.2	-

A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter
47	89.7	85.7	85.6	32.0	-
47	80.3	77.6	78.9	24.0	-
47	80.6	76.8	77.2	27.7	-
47	89.2	84.5	86.2	24.0	-
48	73.6	69.4	71.1	19.4	-
48	73.5	69.3	70.1	22.3	-
48	73.5	68.8	71.3	14.7	-
48	78.3	75.1	75.9	26.9	-
48	66.4	64.2	66.0	17.1	4.81
49	76.3	72.0	73.6	20.6	-
50	63.1	59.9	60.7	22.4	-
50	83.0	79.5	79.9	27.8	-
51	75.4	72.1	71.4	33.8	-
52	65.7	61.6	63.8	15.9	
52	75.4	72.3	72.5	27.5	4.41
53	84.8	82.2	80.5	38.6	-

APPENDIX I (Cont'd)

A yr	V_{max} liter	V_{min} liter	M kg	F kg	V_h liter
53	77.6	74.6	75.4	28.0	-
54	91.8	88.1	87.8	36.8	-
54	69.7	65.0	66.8	16.8	-
57	72.7	70.6	72.0	20.7	-
57	77.5	74.1	74.2	[illegible]	4.81
57	97.3	93.1	94.3	28.1	5.00
59	77.8	74.2	75.6	22.9	5.21
63	73.8	70.0	70.1	26.4	-
67	73.8	69.3	70.1	22.9	-

FIG. 1



LESS VITAL CAPACITY
FILLED LUNGS
DENSITY [kg/liter]
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.1
0.2
0.3
0.5
F/M

FIG. 2

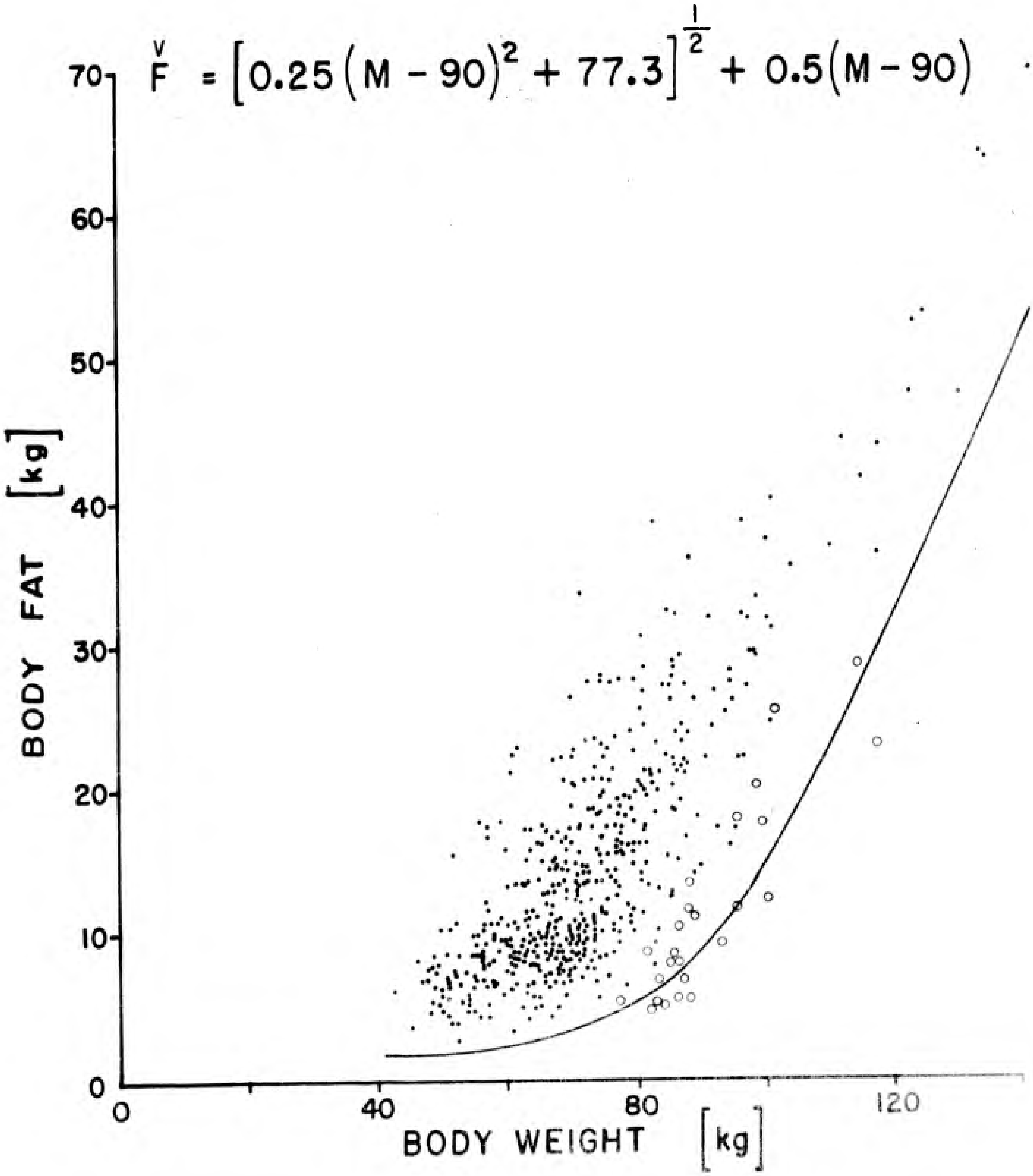
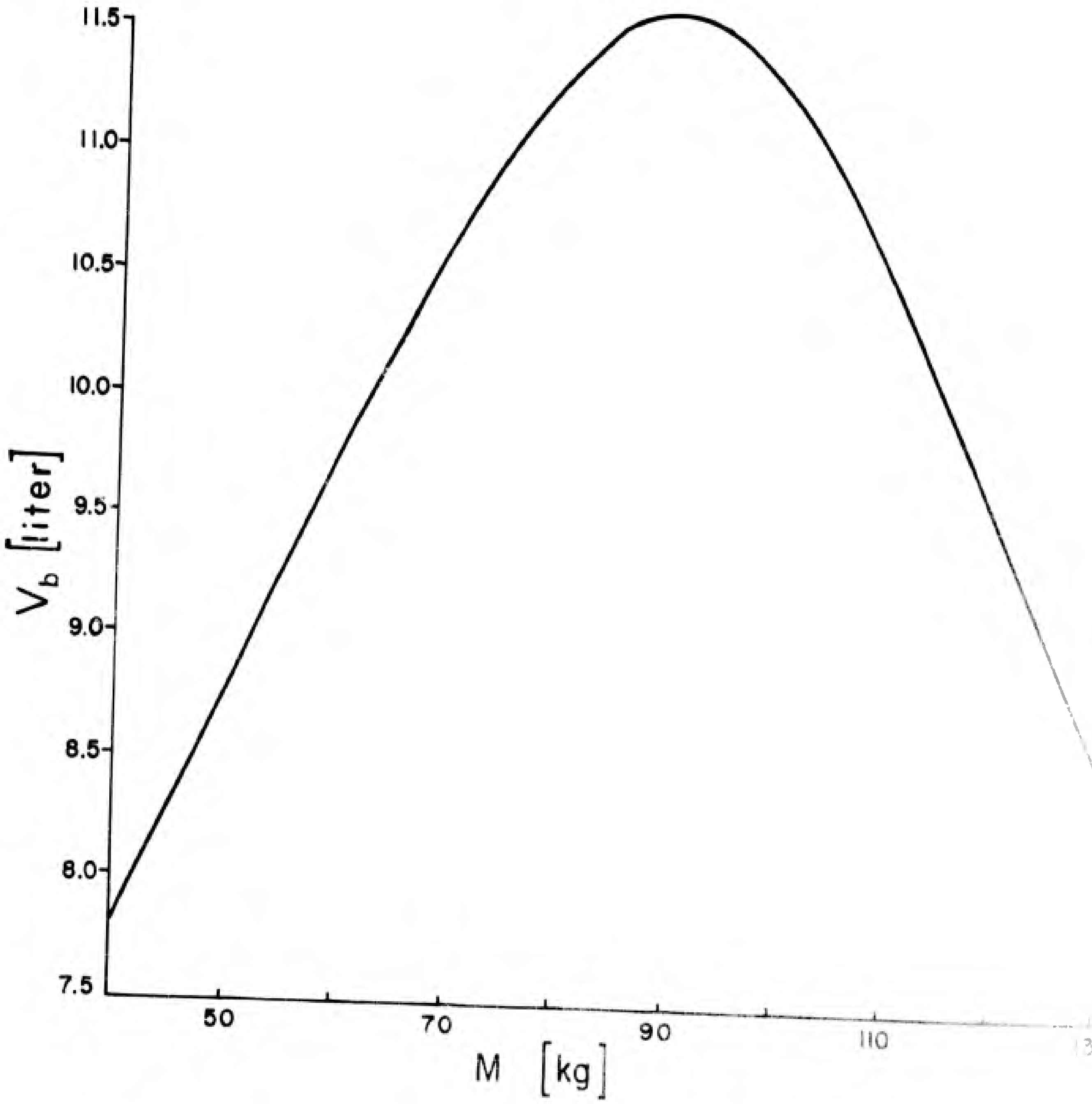

$\check{F} = \left[0.25(M-90)^2 + 77.3\right]^{\frac{1}{2}} + 0.5(M-90)$
BODY FAT [kg]
BODY WEIGHT [kg]
0
10
20
30
40
50
60
70
40
80
120

FIG. 3



Medical Research and Nutrition Laboratory Project 6-60-11-001 Report No. 256

PHYSIOLOGICAL BASIS OF FLOATING IN WATER

R. W. Allard, K. S. K. Chinn, H. J. Krzywicki, T. H. Allen

15 pp, 3 Figs., 2 Tables, 1 Appendix 22 February 1961 UNCLASSIFIED

Specifications are derived for the volume of air necessary to float men with their heads out of water to the level of the first thoracic vertebrum. The derivation is based on (a) proportions of body fat, (b) its density and (c) that of the lean body mass together with (d) residual lung volumes. In order to float all body types of men, including large lean men, 11.6 liters of submerged air are believed necessary. It is shown that loading with wet clothing and typical weapons can increase this requirement to upwards of 23 liters of air.

1. Applied Physiology 2. Body Composition 3. Stream Crossings

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