

INDICES OF OBESITY DERIVED FROM BODY WEIGHT AND HEIGHT

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The relation between body weight and mortality, particularly from cardiovascular disease and diabetes, is well established (Society of Actuaries, 1959; Preston and Clarke, 1966). A reliable, practicable, and generally acceptable index of obesity would therefore have important epidemiological, actuarial, and clinical applications; but many difficulties stand in the way of providing such an index.

Fat has a very different density from muscle and bone, so that one of the best indices is the specific gravity of the whole body, measured by water displacement. It is impracticable, however, to take the necessary measurements outside a specialized laboratory—total immersion would generally be regarded as too high a price to pay for a life policy—and even in the laboratory the measurements are not altogether reliable because of the varying volumes of gases in the air passages and the gastrointestinal tract. In busy clinical practice and in large-scale epidemiological surveys sophisticated methods of “somatotyping”, whether based on photography (Sheldon, Stevens, and Tucker, 1940) or on anatomical measurements (Parnell, 1958), are also impracticable because of the time they take, apart altogether from questions of their reliability and interpretation. The measurement of skin-fold thickness has its uses but is subject to considerable site and observer variation and has the disadvantage that it demands what in epidemiological surveys may be an unacceptable amount of undressing (Edwards, Hammond, Healy, Tanner, and Whitehouse, 1955).

Because of these difficulties, weight in relation to height is commonly used as an index. Indices based on these two measurements have the unavoidable disadvantage that they take no account of muscularity or bone structure, but they have the great merit that the measurements themselves can be made easily, quickly, and with a fair degree of accuracy.

The three indices combining weight (W) and height (H) that have most often been used are:

$$\frac{W}{H},$$

$$\frac{W}{H^2}$$

(sometimes called Quetelet's index),

$$\text{and } \frac{H}{W^{\frac{1}{3}}}$$

(often called the ponderal index).

Billewicz, Kemsley, and Thomson (1962) examined some of the properties of these indices. They found that all three appeared to correlate satisfactorily with relative adiposity, as estimated from body-density measurements. But when they were put to the test on weight, height, and age data for 6,000 primigravidae attending the Aberdeen Maternity Hospital, the simple ratio $\left(\frac{W}{H}\right)$ appeared to underestimate and the ponderal index $\left(\frac{H}{W^{\frac{1}{3}}}\right)$ to overestimate the amount of obesity among the short as compared with the tall women. Quetelet's index $\left(\frac{W}{H^2}\right)$ showed very little bias in relation to height, but was considered unsatisfactory because it is tedious to calculate when large numbers of cases are involved and because its numerical value depends upon the units of measurement employed (e.g. inches and pounds, or centimetres and kilograms).

In this paper we re-examine the credentials of indices based upon weight and height, confirm that $\frac{W}{H^2}$ is much the best of them, suggest a method for calculating that index quickly without resort to an electronic computer, and illustrate its use in relation to original data on obesity and social class.

SOURCE OF DATA

The data used in the paper are derived from an epidemiological study of the distribution of arterial

pressure in an industrial population (Lowe and McKeown, 1962; Lowe, 1964; Khosla and Lowe, 1965). They relate to more than 5,000 men employed by a large electrical engineering firm in Birmingham. The heights and weights of the men were measured and their blood pressures taken as they attended a mobile mass-radiography unit when it visited the firm in March, 1960. The men were asked to remove their coats, waistcoats, and shoes before they were measured. Their weights were taken on a large spring balance and recorded to the nearest pound; their heights were measured against a standard wall-scale and recorded to the half-inch below the observed point. All occupations from works manager to serviceman were included and the measurements can be accepted as reasonably representative of men employed in industry in the Midlands at that time.

THEORETICAL CONSIDERATIONS

We shall focus attention on three indices of obesity derived from weight and height:

$$I_1 = \frac{W}{H}$$

$$I_2 = \frac{W}{H^2} \times 100$$

$$I_3 = \frac{W}{H^3} \times 10,000$$

The index I_3 is, of course, another way of expressing the ponderal index $\left(\frac{H}{W^{\frac{1}{3}}}\right)$. In its more usual form the ponderal index has the disadvantage that it is negatively correlated with weight and so decreases with increasing obesity. We shall use the form $\frac{W}{H^3}$ to bring it into line with the other two indices, in which weight occurs in the numerator.

It seems clear that, in the general population, short persons are no more likely to be obese than tall ones (Billewicz and others, 1962). To be acceptable, therefore, any index of obesity derived from measurements of weight and height will need to satisfy the following two criteria:

- (1) It must be highly correlated with weight;
- (2) It must be independent of height (in the sense that for persons of standard weight at different heights the numerical value of the index should be the same).

Kemsley, Billewicz, and Thomson (1962) have shown that body weight and height are linearly related. The predicted standard weight (\bar{W}) for a

given height (H) can therefore be represented by the regression equation:

$$\hat{W} = \bar{W} + b (H - \bar{H}) \dots \dots \dots (A)$$

where \bar{W} is the mean weight, \bar{H} the mean height, and b the regression coefficient of weight on height.

To satisfy the criterion of independence of height, the obesity index will need to be invariant along the regression of standard weight on height. If we define the index as a function of weight and height of the general form $I = \frac{W}{H^n}$, where n is the power to which H must be raised to meet this criterion, it follows that:

$$I = \frac{\hat{W}_a}{H_a^n} = \frac{\hat{W}_b}{H_b^n} \dots \dots \dots (B)$$

where a and b are any two points along the regression of standard weight on height. (I_1 , I_2 , and I_3 are particular forms of the general index $\frac{W}{H^n}$ defined above.) From equation (B), taking log to the base 10, it follows that:

$$n^* = \frac{\log \hat{W}_b - \log \hat{W}_a}{\log H_b - \log H_a} \dots \dots \dots (C)$$

Let us apply these considerations to the 617 men aged 20-24 in the Birmingham sample. Their mean weight was 154.5 (s.d. 21.6) lb., their mean height was 68.85 (s.d. 2.62) in., and the regression coefficient of weight on height was 4.30. Substituting these values in equation (A) we get:

$$\hat{W} = 154.5 + 4.30 (H - 68.85)$$

If we now take 61.00 and 76.71 in. ($H \pm 3$ s.d.) as the extreme ends of the height distribution for this age group, we obtain from equation (A) predicted weights of 120.7 and 188.3 lb. for those extremes of height. Substituting these values in equation (C) we get:

$$n = \frac{\log 188.3 - \log 120.7}{\log 76.71 - \log 61.00} = 1.94$$

This theoretical approach clearly favours the index $I_2 \left(\frac{W}{H^2}\right)$, at least for the age group 20-24. We will now compare the performance of I_2 with that of I_1 and I_3 for other age groups in the Birmingham industrial population.

* In more general terms, the power "n" is the regression coefficient of log W on log H (i.e. $\log W = \log I + n \log H$).

Age Group	15-19				20-24				25-29				30-34				35-39		
Number	459				617				633				597				633		
Indices	H	W	I ₁	I ₂	H	W	I ₁	I ₂	H	W	I ₁	I ₂	H	W	I ₁	I ₂	H	W	
W	.59				.52				.43				.52				.53		
I ₁	.37	.97			.28	.97			.19	.97			.30	.97			.30	.97	
I ₂	.075*	.85	.95		-.023	.84	.95		-.100	.85	.96		.017	.86	.96		.004	.85	
I ₃	-.24	.63	.80	.95	-.32	.63	.81	.95	-.36	.68	.85	.96	-.27	.67	.83	.96	-.29	.65	

* Italic figures are not significant at the conventional 5 per cent. level.

Table I gives the zero order correlations between all possible pairs of the variables H, W, I₁, I₂, and I₃ for each of the ten 5-yearly age groups from 15 to 65 years. The few correlation coefficients which are not significant at the 5 per cent. level are shown in italics. For each age group I₁, I₂, and I₃ satisfy the first criterion for an acceptable index of obesity—they are all highly correlated with weight. In this respect I₁ has the highest correlations ($r_{1,w} \approx 0.97$), I₂ comes next with correlations ranging from 0.83 to 0.86, while I₃ has correlations that are consistently and appreciably lower than the other two (ranging from 0.60 to 0.68). However, I₂ alone satisfies the second criterion, that of being independent of height. For each age group I₁ is positively and I₃ negatively and quite highly correlated with height ($r \approx +0.3$ and -0.3 respectively). In comparison, the correlations between I₂ and height are all extremely low ($r < 0.1$) and except for one age-group are not significant. As would be expected, the three indices are themselves highly correlated with one another (r from 0.79 to 0.96).

Table II examines empirically the relative merits of the three indices in relation to standard weights (\hat{W}) at specified heights for the age group 20 to 24 years. The standard weights at the given heights are derived from equation (A). The values of the three indices have been calculated for standard weight at each of the seven specified heights. The figures in brackets express the value of the index at each of those heights as a percentage of the corresponding value at 63 in. For I₁ the percentage difference between the extreme heights is 17.6, for I₂ it is 0.9, and for I₃ it is 16.9. The Table thus confirms that only I₂ is unbiased in relation to height; I₁ substantially overestimates obesity among taller persons and I₃ overestimates it among shorter persons.

CALCULATION OF THE INDEX I₂

An index of obesity, however appropriate, will be of restricted use if a great deal of tedious arithmetic is involved in its calculation. The exact method of calculating the mean and standard deviation of I₂ for a large population is certainly tedious and costly.

TABLE II
STANDARD WEIGHTS AT SPECIFIED HEIGHTS
Males aged 20-24

Height (in.)	63"	65"	67"	69"	71"	73"	75"	Correlations Height × Index
Standard Weight \hat{W} (lb.)	129	138	147	155	164	172	181	
$\frac{\hat{W}}{H} = I_1$ (Per cent. of 63" value)	2.05 (100)	2.12 (103.4)	2.19 (106.8)	2.25 (109.8)	2.31 (112.7)	2.36 (115.1)	2.41 (117.6)	+0.28
$\frac{\hat{W}}{H^2} 100 = I_2$ (Per cent. of 63" value)	3.25 (100)	3.27 (100.6)	3.27 (100.6)	3.26 (100.3)	3.25 (100)	3.23 (99.4)	3.22 (99.1)	-0.02
$\frac{W}{H^3} 10,000 = I_3$ (Per cent. of 63" value)	5.16 (100)	5.02 (97.3)	4.89 (94.8)	4.72 (91.5)	4.58 (88.8)	4.42 (85.7)	4.29 (83.1)	-0.32

GHT, BODY WEIGHT, AND THE INDICES I_1 , I_2 , I_3
15-64

40-44				45-49				50-54				55-59				60-64			
494				551				478				399				261			
I_1	W	I_1	I_2	H	W	I_1	I_2	H	W	I_1	I_2	H	W	I_1	I_2	H	W	I_1	I_2
50				.52				.49				.59				.46			
28	.97			.29	.97			.27	.97			.36	.96			.22	.97		
007	.86	.96		.004	.86	.96		-.076	.86	.96		.046	.83	.95		-.063	.85	.96	
29	.67	.83	.96	-.28	.67	.84	.96	-.29	.68	.84	.96	-.28	.60	.79	.95	-.33	.68	.84	.96

Mean weight (\bar{W}) divided by mean height squared (\bar{H})² will give an approximate value for the mean of the index (\bar{I}_2). This approximation was used by the American Army Authorities responsible for the statistical study of men enlisted for the first world war (quoted by Cathcart, Hughes, and Chalmers, 1935). For statistical purposes, however, the mean value of I_2 is of limited use unless the standard deviation of the index is also known. It can be shown (Cochran, 1953) that the standard deviation of a function of two variables of the form $\frac{\bar{W}}{\bar{H}^2} \times 100$ is:

$$s.d. I_2 = \frac{100}{\bar{H}^3} \sqrt{\bar{H}^3 S_w^2 + 4 \bar{W}^3 S_H^2 - 4 r_{WH} \bar{H} \bar{W} S_w S_H}$$

where r_{WH} is the correlation coefficient of weight

and height and S_w and S_H are the standard deviations of weight and height respectively.

In Table III we consider the "goodness" of the approximate methods of calculating $\bar{I}_2 \left(\frac{\bar{W}}{\bar{H}^2} \times 100 \right)$ and of the standard deviation of I_2 by applying them to the Birmingham data. The results as calculated by exact and approximate methods are in excellent agreement.

The fact that the absolute value of the index I_2 depends upon the units of measurement employed (as, of course, must all indices based on height and weight) has been cited as a reason for not recommending its general use (Billewicz and others, 1962). This is not a serious objection. The index as calculated in pounds and inches is linearly related to the index as calculated in kilograms and centimetres by a factor of 14.22; so the one value may readily be converted to the other.

TABLE III
MEAN AND STANDARD DEVIATION OF BODY WEIGHT (lb.), STANDING HEIGHT (in.), AND OBESITY INDEX I_2 , CALCULATED BY EXACT AND APPROXIMATE METHODS

Age Group (yrs)	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64
Number of Readings (N)	459	617	633	597	633	494	551	478	399	261
Mean Body Weight (\bar{W})	144.6	154.5	160.2	161.4	163.2	162.5	161.2	158.3	157.2	154.4
s.d. (S_w)	22.29	21.64	23.16	24.32	23.41	23.82	24.89	23.91	24.84	23.18
Mean Height* (\bar{H})	68.3	68.6	68.5	68.0	67.7	67.4	67.1	66.7	66.4	65.6
s.d. (S_H)	2.86	2.62	2.59	2.60	2.59	2.57	2.64	2.62	2.92	2.58
Correlation W x H (r_{WH})	.59	.52	.43	.52	.53	.50	.52	.49	.59	.46
I_2 (exact) = $\frac{\sum \frac{W}{H^2} \times 100}{N}$	3.09	3.29	3.41	3.49	3.55	3.58	3.58	3.55	3.55	3.60
s.d. I_2	.39	.39	.45	.45	.43	.45	.48	.47	.45	.48
I_2 (approx.) = $\frac{\bar{W}}{\bar{H}^2} \times 100$	3.10	3.28	3.41	3.49	3.56	3.58	3.58	3.56	3.57	3.59
s.d. I_2	.39	.39	.45	.45	.43	.45	.47	.47	.45	.48

* Standing height was measured to $\frac{1}{4}$ " below; for comparison with other data 0.25 should therefore be added to the mean. The average effect on the index is to decrease I_2 by 0.02. No adjustment for centring has been made on this Table because the calculation by the exact method, which was carried out by computer, was based on observed readings.

APPLICATION OF I_2 TO THE PROBLEM OF OBESITY AND SOCIAL CLASS

Despite an unparalleled improvement in the nutrition of the population of Britain since the beginning of the present century, there are still appreciable differences between the heights and weights of the different social classes, not only in childhood but also in adult life (Clements and Pickett, 1954; Tanner, 1962). In view of the well-known relation between mortality from coronary disease and both obesity (Dawber, Kannel, Revot-skie, Stokes, Kagan, and Gordon, 1959) and social class (Morris, Heady, Raffle, Roberts, and Parks, 1953), it would be of considerable interest to know whether or not the social classes differ also in respect of obesity. The paucity of evidence on this point is in part due to confusion about what constitutes a satisfactory index of obesity for epidemiological purposes.

In Table IV the men in the Birmingham survey have been grouped by age into monthly staff (salary paid in monthly instalments), weekly staff (salary paid in weekly instalments), and wage-earners (men paid a weekly wage varying in relation to hours worked, overtime, piece work, etc.). These sub-divisions would be expected to correspond broadly with social class and general standard of living in the works population. The trend of weight with age is quadratic, at first increasing and then decreasing with increasing age (Fig. 1). The corresponding trend of height with age is linear, with a negative slope (Fig. 2, opposite). But the three sub-groups differ strikingly in mean weight and height. At each age the monthly staff are from 5 to 9 lb. heavier than the wage-earners (Fig. 1). They are

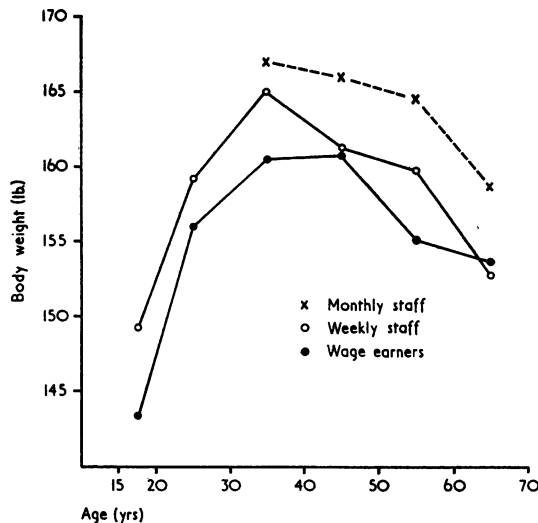


FIG. 1.—Body weight and works status.

also about 1.5 in. taller (Fig. 2). And for both measurements the weekly staff occupy an intermediate position. The great majority of the monthly paid staff and many of the weekly staff have sedentary occupations, whereas most of the wage-earners are in jobs calling for moderate and in some cases for heavy physical effort. It is of some importance, therefore, to know whether the monthly and weekly staff are not only heavier and taller but are also more obese than the physically more active wage-earners. According to the index I_2 , this is not so, in fact wage-earners appear to be

TABLE IV
MEAN WEIGHT, HEIGHT, INDEX I_2 , AND WORKS STATUS
Males aged 15–69

Measurement	Works Status	Age Group (yrs)					
		15–19	20–29	30–39	40–49	50–59	60–69
Fig. 1 Mean Weight (\bar{W}) (lb.)	Monthly staff	—	—	167.4	166.3	164.6	158.9
	Weekly staff	149.1	159.1	165.5	161.5	159.9	152.8
	Wage earners	143.3	155.8	160.6	161.2	155.3	153.2
Fig. 2 Mean Height (\bar{H}) (in.)	Monthly staff	—	—	69.3	68.5	68.2	67.1
	Weekly staff	69.2	69.4	68.7	67.8	67.2	66.1
	Wage earners	68.3	68.2	67.7	67.2	66.4	65.3
Fig. 4 $I_2 = \frac{\bar{W}}{\bar{H}^2} \times 100$ (lb. per in. ²)	Monthly staff	—	—	3.49	3.54	3.53	3.53
	Weekly staff	3.11	3.30	3.51	3.52	3.54	3.50
	Wage earners	3.07	3.35	3.50	3.57	3.53	3.60

Figures in brackets are the number of readings. Mean heights are adjusted for the group interval.

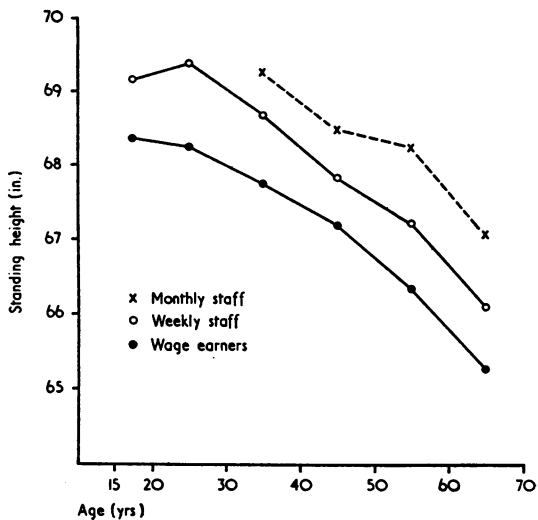


FIG. 2.—Standing height and works status.

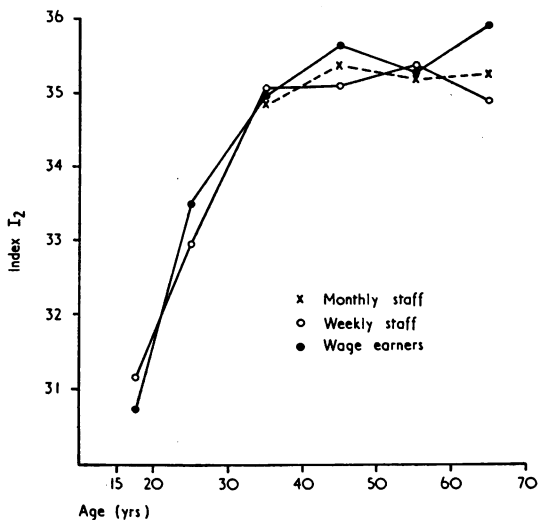


FIG. 4.—Index $I_2 = \frac{W}{H^2} \times 10,000$ and works status.

substantially more “obese” than monthly staff (Fig. 3).

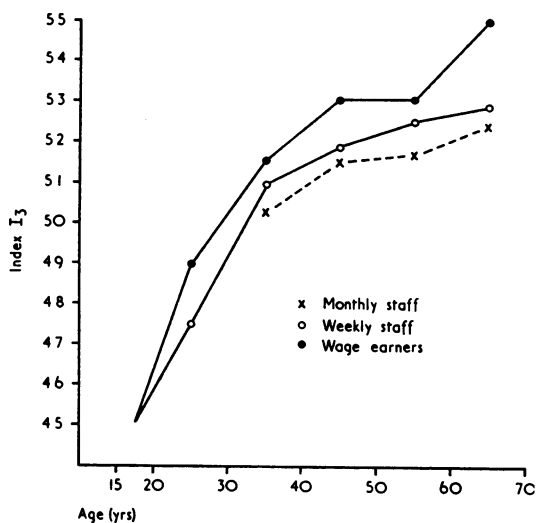


FIG. 3.—Index $I_3 = \frac{W}{H^3} \times 10,000$ and works status.

The index I_3 , on the other hand, suggests that the three groups are not differentiated in respect of obesity (Fig. 4). The two indices clearly give contradictory results.

An alternative method of comparing the trend of obesity in the three population sub-groups would be to adjust the mean body weights to a common height. The pooled, within-age, regression coefficient of weight on height for our data was

4.55 lb. per inch. For any sub-group, therefore, weight adjusted to a height of 68 in. would be calculated as follows:

$$\text{Adjusted body weight} = \bar{W} - 4.55 (H - 68)$$

We find that the trend displayed by this method (Fig. 5) agrees very closely with the trend as indicated by I_2 (Fig. 4), and it is reasonable to conclude that monthly and weekly staff are much heavier than the physically more active wage-earners, not because of their sedentary occupations but because of their greater height.

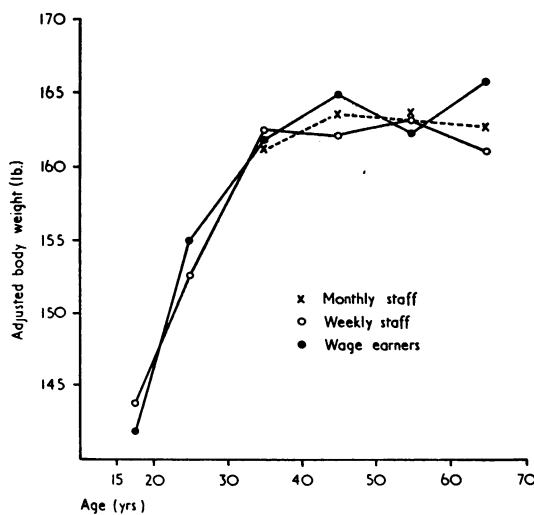


FIG. 5.—Adjusted body weights (at 68" height) and works status.

DISCUSSION

How obese a person is and how much he is overweight are not quite the same thing. Obesity implies an excessive amount of body fat, but a man may be overweight for his height because he is more muscular than average. Nevertheless, being obese and being overweight are closely related: if a man is obese he will almost certainly be overweight, and if he is much overweight he will certainly be obese. Because there is, as yet, no reliable method of measuring body fat which can be applied in the difficult circumstances of a large-scale epidemiological investigation, recourse must be had to indices of overweightness. A satisfactory index must, necessarily, be highly correlated with weight.

We have shown that $I_1 \left(\frac{W}{H} \right)$ is very highly correlated with weight ($r \approx 0.97$). This index is unsatisfactory, however, because it is also positively correlated with height ($r \approx +0.3$), and there is good reason to believe that in the general population obesity is independent of height (Billewicz and others, 1962). The index $I_3 \left(\frac{W}{H^2} \right)$ has the double disadvantage that it not only has a substantially lower correlation with weight ($r \approx 0.6$) but also has a negative correlation with height ($r \approx -0.3$). The index $I_2 \left(\frac{W}{H^2} \right)$ alone is both highly correlated with weight ($r \approx 0.85$) and consistently independent of height. For this reason, and because it can be reliably estimated for grouped data from mean weight and mean height squared, we consider it to be the index of choice for epidemiological purposes.

It may be asked why the method of adjusting weight to a standard height is not preferable. The reason is that the procedure of adjusted body weight assumes that the regression lines of weight on height for the populations under comparison are parallel. If they are not, the difference between the adjusted weights will vary accordingly to the standard height chosen. And quite often they are not. For example, the regression coefficient of weight (lb.) on height (in.) for middle-aged men (40-49) in the Birmingham industrial population in 1960 was 4.7; but for a sample of men of the same age, working in factories and mines in 1943, it was 3.8 (Kemsley, 1950). It would not be permissible, therefore, to compare the relative obesity of these two populations by the method of adjusted body weight. The index I_2 , however, would be entirely appropriate.

SUMMARY

The index $\frac{W}{H^2} \times 100$, where W is the weight and H the height of a person, is found to satisfy

the following criteria necessary for an epidemiological index of obesity:

- (1) It is highly correlated with body weight ($r \approx 0.85$).
- (2) It is shown to be independent of height on the basis of both theoretical and empirical considerations.
- (3) Its mean and standard deviation can readily be calculated by approximate methods which give results in excellent agreement with the much more laborious exact methods.
- (4) It can readily be converted from pounds and inches to kilograms and centimetres.

The index is applied to measurement of height and weight in an industrial population in the Midlands. It is shown that although senior staff are much heavier, age for age, than wage-earners, they are not necessarily more obese, the greater part, perhaps all, of their excess weight being due to their greater height.

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