JACC Vol. 20, No. 5
November 1, 1992:1251–60

Left Ventricular Mass and Body Size in Normotensive Children and Adults: Assessment of Allometric Relations and Impact of Overweight

GIOVANNI DE SIMONE, MD, STEPHEN R. DANIELS, MD, PHD,*
RICHARD B. DEVEREUX, MD, FACC, RICHARD A. MEYER, MD, FACC,*
MARY J. ROMAN, MD, FACC, ORESTE DE DIVITIIS, MD,† MICHAEL H. ALDERMAN, MD‡

New York, New York; Cincinnati, Ohio, and Naples, Italy

Objectives. This study was designed to determine the most appropriate method to normalize left ventricular mass for body size.

Background. Left ventricular mass has been normalized for body weight, surface area or height in experimental and clinical studies, but it is uncertain which of these approaches is most appropriate.

Methods. Three normotensive population samples—in New York City (127 adults), Naples, Italy (114 adults) and Cincinnati, Ohio (444 infants to young adults)—were studied by echocardiography. Relations of left ventricular mass to body size were similar in all normal weight groups, as assessed by linear and nonlinear regression analysis, and results were pooled (n = 611).

Results. Left ventricular mass was related to body weight to the first power (r = 0.88), to body surface area to the 1.5 power (r = 0.88) and to height to the 2.7 power (r = 0.84), consistent with expected allometric (growth) relations between variables with linear (height), second-power (body surface area) and volumetric (left ventricular mass and body weight) dimensions. Strong residual relations of left ventricular mass/body surface area to body surface area (r = 0.54) and of ventricular mass/height to height (r = 0.72) were markedly reduced by normalization of ventricular mass for height$^{2.7}$ and body surface area$^{1.5}$. The variability among subjects of ventricular mass was also reduced ($p < 0.01$ to $p < 0.002$) by normalization for body weight, body surface area, body surface area$^{1.5}$ or height$^{2.7}$ but not for height. In 20% of adults who were overweight, ventricular mass was 14% higher ($p < 0.001$) than ideal mass predicted from observed height and ideal weight; this increase was identified as 14% by left ventricular mass/height$^{2.7}$ and 9% by ventricular mass/height, whereas indexation for body surface area, body surface area$^{1.5}$ and body weight erroneously identified left ventricular mass as reduced in overweight adults.

Conclusions. Normalizations of left ventricular mass for height or body surface area introduce artifactual relations of indexed ventricular mass to body size and errors in estimating the impact of overweight. These problems are avoided and variability among normal subjects is reduced by using left ventricular mass/height$^{2.7}$. Simple nomograms of the normal relation between height and left ventricular mass allow detection of ventricular hypertrophy in children and adults.

(J Am Coll Cardiol 1992;20:1251–60)

Evidence that increased left ventricular mass predicts cardiovascular morbidity and mortality in patients with arterial hypertension (1,2) among members of the general population (3,4) and in patients with chronic renal failure (5) or coronary artery disease (6) has increased interest in assessing ventricular anatomy by methods more precise than the 12-lead electrocardiogram (ECG) (7). Echocardiography is often used for this purpose because of its noninvasive nature and moderate cost and because it yields reasonably stable normal limits for left ventricular dimensions in different laboratories (8–11). Recent evidence that high normal values of left ventricular mass predict subsequent blood pressure evaluation in children and adults (12,13) further increases the appeal of measuring ventricular anatomy.

To identify abnormalities of ventricular mass or other measures of heart size, the relation between heart and body size should be taken into account (14–16). Although ventricular weight is usually normalized for body weight in experimental studies, human ventricular mass has generally been indexed for body surface area or height (1–3,8,9,17–21). These methods of indexing may identify different prevalences of left ventricular hypertrophy in obese subjects and in disease states associated with obesity such as hypertension. Moreover, although the relations among body surface area, height and weight are not linear, the division of left ventricular mass by these variables implicitly assumes linear relations with zero intercepts. On the basis of the observa-

From the Department of Medicine, The New York Hospital–Cornell Medical Center, New York, New York; *Division of Cardiology, Children's Hospital Medical Center, Cincinnati, Ohio; †Division of Cardioangiology, Institute of Internal Medicine and Metabolic Diseases, 2nd Medical School, Naples, Italy and ‡Department of Epidemiology and Social Medicine, Albert Einstein College of Medicine, Bronx, New York. This study was supported in part by Grant HL 18323 from the National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Maryland and by a Lederle International Scientist Award from Lederle, Inc., Pearl River, New Jersey.

Manuscript received December 23, 1991; revised manuscript received May 1, 1992, accepted May 13, 1992.

Address for correspondence: Richard B. Devereux, MD, Division of Cardiology, Box 222, The New York Hospital–Cornell Medical Center, 525 East 68 Street, New York, New York 10021.

0735-1097/92/$5.00

Table 1. Age and Measures of Body Size in Two Groups of Normotensive Adults

	New York (n = 127)	Naples (n = 114)	p Value
Normal-weight			
No. of subjects	100	87	
Gender (M/F)	62/38	55/32	NS
Age (yr)	45 ± 13	40 ± 12	<0.01
Body surface area (m^2)	1.81 ± 0.21	1.69 ± 0.17	<0.0001
Body weight (kg)	69 ± 12	63 ± 11	<0.0002
Body height (m)	1.72 ± 0.10	1.65 ± 0.08	<0.0001
Body mass index	23.3 ± 2.7	22.9 ± 2.9	NS
Systolic blood pressure (mm/Hg)	124 ± 13	122 ± 13	NS
Diastolic blood pressure (mm/Hg)	76 ± 9	77 ± 6	NS
LV mass index (g/m^2)	79 ± 20	78 ± 16	NS
Overweight			
No. of subjects	27	27	
Gender (M/F)	9/18	9/18	NS
Age (yr)	46 ± 11	43 ± 13	NS
Body surface area (m^2)	1.94 ± 0.23	1.85 ± 0.20	NS
Body weight (kg)	86 ± 16	80 ± 12	NS
Body height (m)	1.67 ± 0.10	1.63 ± 010	NS
Body mass index	30.6 ± 3.2	30.0 ± 2.2	NS
Systolic blood pressure (mm Hg)	127 ± 10	125 ± 11	NS
Diastolic blood pressure (mm Hg)	78 ± 7	78 ± 6	NS
LV mass index (g/m^2)	76 ± 22	76 ± 19	NS

F = female; LV = left ventricular; M = male; NS = not significant (p < 0.05). See text for description of study groups.

tions of McMahon (22) for other organs, one would expect that the relations of left ventricular mass to measures of body size would approximate the mathematic relations among variables with different dimensions; that is, three-dimensional for ventricular mass and body weight, two-dimensional for body surface area and one-dimensional for body height. However, few data are available on the ability of various methods of normalization to reduce the variability of left ventricular mass among normal subjects (8) or to detect deviations in ventricular mass in overweight patients (9,23).

Thus, the present study was undertaken to compare the relations of left ventricular mass to body surface area, height and weight in three different population groups of normotensive subjects with a wide age range and to determine the most appropriate method to remove the effect of normal variation in body size from the clinical evaluation of left ventricular hypertrophy.

Methods

Subjects. *New York group (Table 1).* This group, studied at The New York Hospital–Cornell Medical Center, consisted of 127 adults (56 women and 71 men, 36% black, with a mean age of 45 ± 12 years) who were representative of a cohort of normotensive members (blood pressure <140/90 mm Hg on at least three separate occasions) of a large employed population in New York City that has been studied longitudinally by echocardiography and other methods since 1981 (8,13,18,20). The mean body mass index of the total group was 25 ± 4 kg/m^2. Twenty-seven subjects (18 women and 9 men) had a body mass index exceeding partition values used to recognize overweight (24) (27.8 kg/m^2 in men or 27.3 kg/m^2 in women) and were considered overweight to mildly obese (body mass index 31 ± 3 kg/m^2). No subject had historical, clinical or laboratory evidence of cardiovascular, respiratory, endocrine, hepatic, renal or hematologic disorders; their M-mode echocardiograms met standard criteria of technical quality (25).

Naples group (Table 1). This group consisted of 114 white normotensive volunteers from southern Italy, 87 of normal weight (32 women and 55 men with a mean age of 40 ± 12 years) and 27 who were overweight to mildly obese (18 women and 9 men with a mean age of 43 ± 13 years) who were studied at the Institute of Internal Medicine and Metabolic Diseases of Federico II University of Naples between 1981 and 1987. The normal weight subjects were part of a population sample that met more restrictive criteria, including the absence of a family history of hypertension, athletic training, alcohol consumption or plasma cholesterol levels ≥220 mg/dl. The overweight subjects were similar in gender and age to the New York overweight group and were randomly drawn from a clinical population of consecutive normotensive obese patients studied at Naples who met inclusion criteria applied to the New York group. Table 1 shows that the Naples normal weight subjects were younger

($p < 0.01$) and smaller in body size than the New York group ($p < 0.0002$) but had the same gender distribution, body mass index, blood pressure and left ventricular mass index. No differences existed between the two overweight groups.

Cincinnati group. This group, studied at Children's Hospital Medical Center, Cincinnati, Ohio, consisted of 444 young normal subjects (217 female and 227 male, 27% black), with an age range of 4 months to 23 years, previously reported in part as reference subjects for left ventricular mass values (19). Twenty subjects were considered overweight on the basis of the same body mass index criterion as in adults (24) for subjects older than 16 years and of the upper 95th percentile of body weight at a given height from tables for younger children (26).

Procedures. After informed consent had been obtained under protocols approved in 1979 or later by the Committees on Human Research of the respective institutions, two-dimensionally targeted M-mode echocardiograms were performed with the use of commercially available echocardiographs as previously described (10,11), while subjects were in a partial left decubitus position. Tracings were recorded on strip-chart paper at 50 mm/s. All echocardiograms in the first two groups were coded and were interpreted in blinded fashion by two investigators, one of whom (G.de S.) was one of the readers for all Naples and most New York tracings. Measurements of interventricular septal thickness, posterior wall thickness and left ventricular diastolic dimension were taken at or just below the mitral valve tips, according to both the American Society of Echocardiography and Penn Conventions, and were used to calculate left ventricular mass (27–29). Echocardiograms in the Cincinnati group were measured as previously reported (19), by using American Society of Echocardiography measurements in an anatomically validated formula (29).

Body weight (in kg) and body height (in m) were measured and used to calculate body surface area (in m^2) (30).

Statistical analysis. Data are expressed as mean value ± 1 SD. Chi-square statistics were used to compare gender prevalence and the unpaired Student *t* test, to compare the two adult groups (Naples and New York) and overweight with normal weight subjects. Relations of left ventricular mass to measures of body size were assessed by linear regression analysis. Multivariate analysis was performed by partial correlation and by forward stepwise multiple linear regression procedure. Nonlinear regression analysis was performed to assess the allometric (growth) relation (31) of left ventricular mass to measures of body size by equations of the following type:

$$\text{Left ventricular mass} = b_1 \times \text{measure of body size}^{b2},$$

where b_1 is a regression coefficient reflecting the quantitative relation between variables and ^{b2} is the power of the measure of body size that produces the best fit of the data. In such equations, ^{b2} is defined as the allometric signal of the relation and indicates whether its slope is linear (that is, if $^{b2} = 1$) or curvilinear. The biologic meaning of the regression coefficient is that it indicates the magnitude of the influence of the measure of body size on left ventricular mass (it can also be called the proportionality coefficient), whereas the power indicates the magnitude of the exponential change of left ventricular mass in relation to a measure of body size; that is, the relation is linear if $^{b2} = 1$ but would be steeply curvilinear if $^{b2} = 3$.

Allometric equations were generated by an iterative computer technique seeking to estimate the unknown variables (b_1 and ^{b2}) so that the sum of all the observations of the squared differences between the observed and predicted left ventricular mass values was minimized, producing the highest possible R^2. Confidence intervals for the nonlinear regression analysis were generated by using the final estimates ± SEE × two-tailed test value, alpha = 0.05 *t* values for 609 degrees of freedom (Systat, Inc.).

The coefficients of variation of left ventricular mass, of ventricular mass normalized by each body size variable and of ventricular mass normalized for each measure of body size to the power of its allometric signal (^{b2}) were compared by using the ratio between the variances of the logarithmic transformation of the variables (32). One-factor analysis of variance for randomized blocks was applied to examine the difference between ideal and observed values of ventricular mass in both normal and overweight subjects. Two-way hierarchical analysis of variance was used to detect the impact of gender and overweight on the indexes of left ventricular mass; with this method, the interaction between gender and body mass index was adjusted for both variables and the effect of body mass index was adjusted for gender, whereas that of gender was not adjusted for any other effects.

Relations were initially assessed separately in the New York, Naples and Cincinnati study groups and, as they did not differ, data were pooled to generate confidence limits of the relations between left ventricular mass and the measures of body size.

Results

Normal weight subjects. The Penn Convention and American Society of Echocardiography measurements of left ventricular mass were virtually identical in the pooled data from Naples and New York groups (139 ± 40 vs. 140 ± 37 g). Substitution of left ventricular mass measurements by the Penn Convention for those from American Society of Echocardiography had no substantial effect on the results of any analyses; hence, only measurements obtained from American Society of Echocardiography are reported.

Linear regression analysis. Figure 1 shows the relations between left ventricular mass and each measure of body size (body surface area, body weight and height) in the three groups of normal weight subjects. All the correlations were significant ($p < 0.00001$), and the magnitude was similar in all groups. As a consequence of the nonlinear relations that are visually apparent in Figure 1, normalization of left ventric-

Figure 1. Linear relations of left ventricular mass to measures of body size in three different normal weight population samples from 1) Naples, Italy (**crossed squares**; body surface area r = 0.69, body weight r = 0.67, height r = 0.59, all $p < 0.00001$); 2) New York City (**triangles**; body surface area, r = 0.65, body weight r = 0.63, height r = 0.58, all $p < 0.00001$); and 3) Cincinnati, Ohio (**solid squares**; body surface area r = 0.86, body weight r = 0.87, height r = 0.84, all $p < 0.00001$).

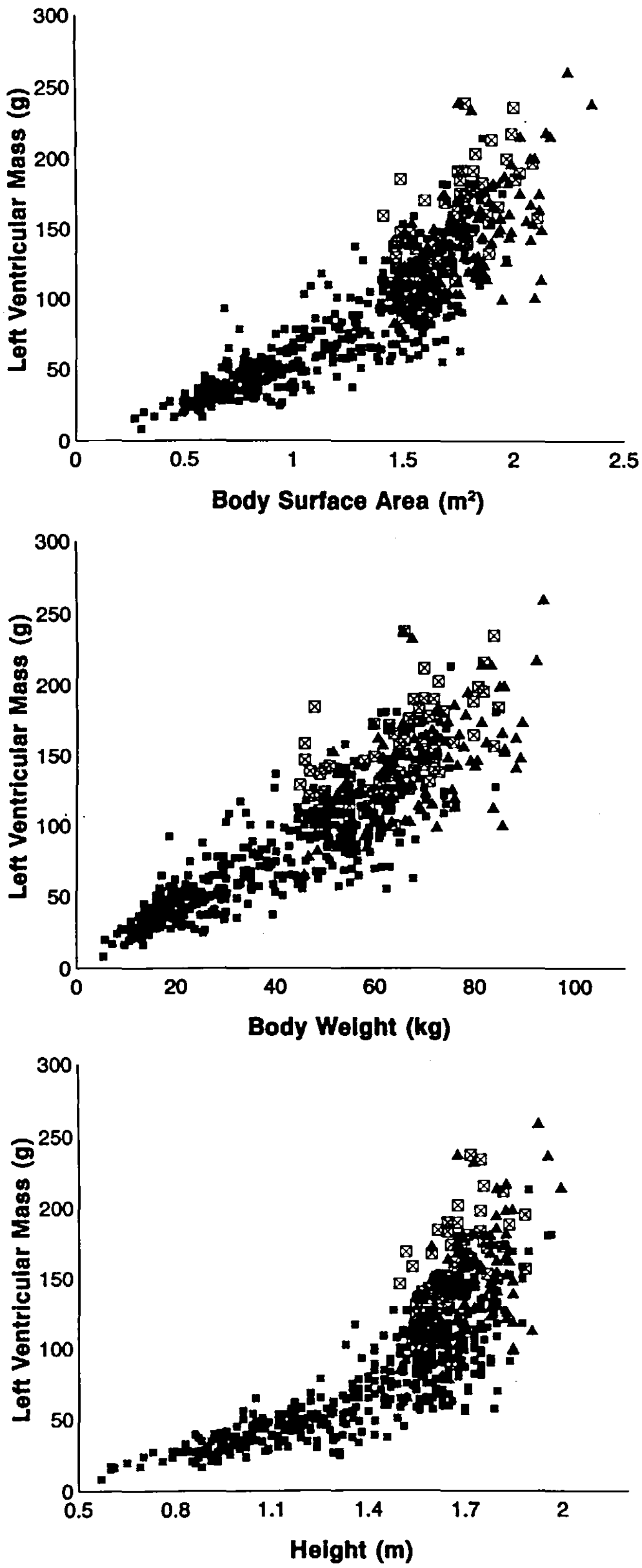

Table 2. Allometric Equations for Predicting Left Ventricular Mass From Measures of Body Size in Normal Weight Subjects

Group	Equations	r
Naples (n = 87)	66 × body surface area$^{1.5}$	0.69
	3.7 × body weight$^{0.89}$	0.67
	41 × height$^{2.5}$	0.59
New York (n = 100)	57 × body surface area$^{1.6}$	0.65
	3.4 × body weight$^{0.88}$	0.62
	36 × height$^{2.6}$	0.58
Cincinnati (n = 424)	58 × body surface area$^{1.3}$	0.86
	3.2 × body weight$^{0.87}$	0.87
	32 × height$^{2.4}$	0.86
Pooled		
Total (n = 611)	LV mass = 58 × body surface area$^{1.5}$	0.88
	LV mass = 2.2 × body weight$^{0.99}$	0.88
	LV mass = 30 × height$^{2.7}$	0.84
Women (n = 278)	LV mass = 57 × body surface area$^{1.4}$	0.84
	LV mass = 3.1 × body weight$^{0.88}$	0.85
	LV mass = 33 × height$^{2.4}$	0.79
Men (n = 333)	LV mass = 62 × body surface area$^{1.5}$	0.90
	LV mass = 2.5 × body weight$^{0.96}$	0.89
	LV mass = 33 × height$^{2.6}$	0.86

LV = left ventricular; all correlations are significant ($p < 0.00001$).

ular mass for the first power of body surface area or height resulted in significant positive relations of indexed ventricular mass with body surface area and height, respectively for ventricular mass/body surface area versus body surface area: (Naples, r = 0.31; New York, r = 0.30; Cincinnati, r = 0.38; for left ventricular mass/height vs. height: Naples and New York, r = 0.41; Cincinnati, r = 0.71; all $p < 0.001$). In contrast, the relation of left ventricular mass to body weight was linear with intercepts near zero (5 to 8 g) in all three groups studied. The relation of left ventricular mass to the measures of body size remained significant in all three groups after adjustment for gender (partial r = 0.33 to 0.87, $0.005 < p < 0.00001$).

Nonlinear regression analysis. The residual relations persisting after normalization for body height or surface area indicated that left ventricular mass was related to body height or surface area to a power >1. These relations were examined by using allometric equations. Left ventricular mass was related to body weight to approximately a power of 1 in all groups, whereas it was related to body surface area to a power approximating 1.5 and to height to a power between 2 and 3 (Table 2). Similar results were obtained when data from all the groups were pooled. Separate data analysis in normal weight men and women revealed similar allometric relations of ventricular mass to measures of body size in the two genders.

Reduction of left ventricular mass variability. As expected from analyses in the individual groups, significant positive relations were found in the pooled group between left ventricular mass/body surface area and body surface area (r = 0.54, $p < 0.00001$) (Fig. 2A) and between ventricular mass/height and height (r = 0.71, $p < 0.00001$) (Fig. 2B), whereas the relation of ventricular mass/body weight to

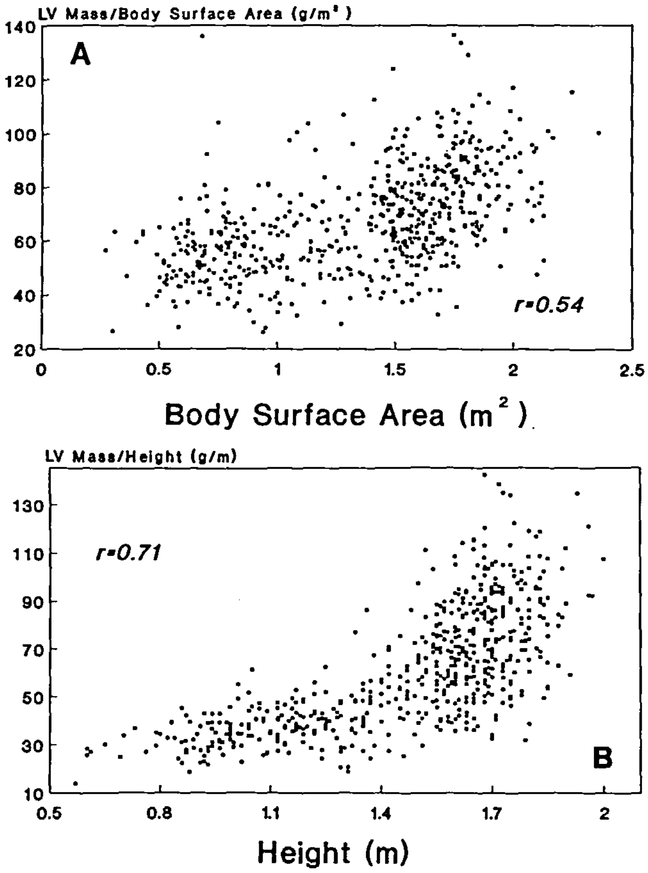

Figure 2. Relations of left ventricular (LV) mass/body surface area to (A) body surface area ($r = 0.54$, $p < 0.00001$) and (B) of left ventricular mass/height to height ($r = 0.71$, $p < 0.00001$) in the pooled group.

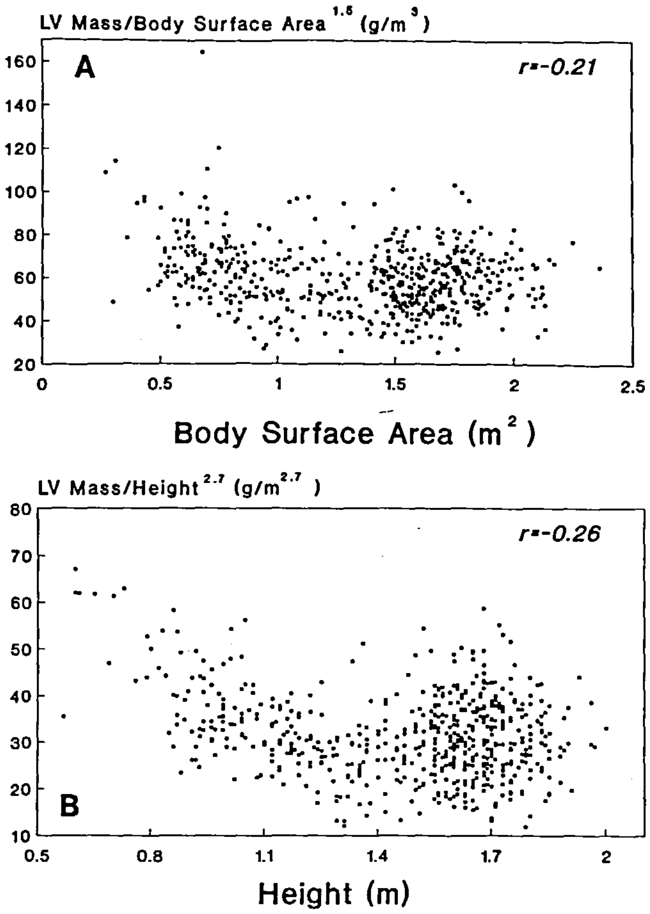

Figure 3. Residual relations are minimized by using the appropriate power of (A) body surface area (1.5, $r = -0.21$, $p < 0.0005$) and (B) height (2.7, $r = -0.26$, $p < 0.00001$) and become similar to that between left ventricular mass/weight and weight (not illustrated, $r = -0.15$, $p < 0.0003$).

body weight was weakly negative ($r = 0.15$, $p < 0.0003$). Use of body surface area$^{1.5}$ and height$^{2.7}$ to normalize ventricular mass reduced residual relations ($r = -0.21$ and -0.26, respectively) and made these relations inverse (Fig. 3, A and B), consistent with the negative relation between ventricular mass/body weight and body weight.

As normalization of anatomic or physiologic variables for body size is expected to reduce their within-group variability, the efficacy of correcting left ventricular mass for measures of body size either to the first power or to their allometric exponents was tested by comparing their coefficients of variation. Table 3 shows that normalizations for body surface area$^{1.5}$ and height$^{2.7}$ were as effective as those for body surface area and body weight in reducing variability of ventricular mass (all $p < 0.01$), whereas that for height was less successful. Results were identical when men and women were analyzed separately.

Impact of overweight on the normal relations between left ventricular mass and body size. Relations between left ventricular mass and measures of body size generated lower and less significant allometric signals in overweight than in normal weight subjects. In the pooled overweight group (74 subjects), left ventricular mass was related to body surface area to approximately a power of 1 ($^{b2} = 1.17$, $r = 0.60$), to height to approximately a power of 2 ($^{b2} = 2.12$, $r = 0.58$) and to body weight to a power <1 ($^{b2} = 0.71$, $r = 0.60$). The relations of ventricular mass to the measures of body size were affected minimally by addition of the 74 overweight subjects to the 611 normal weight subjects ($^{b2} = 0.88$, 1.5 and 2.7 for body weight, body surface area and height, respectively).

Identification of effects of overweight on left ventricular mass. Ideal body surface area was calculated in subjects >17 years old by using the ideal body weight for body height from the 1980 tables of the Metropolitan Life Insurance Company (33) (Table 4). Body surface area calculated in this way was virtually identical to observed body surface area in the normal weight adults and 12% smaller than observed body surface area in 56 of 284 or 20% of adults who were overweight (Table 5). Ideal left ventricular mass (estimated as 58 × ideal body surface area$^{1.5}$ from Table 2) in normoten-

JACC Vol. 20, No. 5
November 1, 1992:1251-60

Table 3. Effect of Normalization of Left Ventricular Mass for Measures of Body Size in Reducing Variability Among Normal Weight Subjects Aged 4 Months to 75 Years

	Coefficient of Variability	Significance vs. Unindexed LV Mass
Infants, children and adolescents (n = 383)		
LV mass	53	—
LV mass/body surface area	27	0.002
LV mass/body weight	26	0.002
LV mass/height	36	0.05
LV mass/body surface area$^{1.5}$	27	0.002
LV mass/height$^{2.7}$	30	0.01
Adults (n = 228)		
LV mass	25	—
LV mass/body surface area	20	0.01
LV mass/body weight	20	0.01
LV mass/height	22	NS
LV mass/body surface area$^{1.5}$	20	0.01
LV mass/height$^{2.7}$	20	0.01

LV = left ventricular.

sive subjects >17 years old was similar to the observed values in normal weight subjects and 14% lower than observed values in overweight subjects (Table 5); the difference between ideal and observed values was statistically significant in overweight subjects ($p < 0.001$). A directionally similar trend between the 18 overweight children and adolescents and 383 with normal weight was not statistically significant.

Influence of gender and overweight on the distribution of left ventricular mass normalized for body size (Table 6). In adults, male gender and overweight were independently associated with higher left ventricular mass. The effect of gender remained striking after most indexing but was reduced for left ventricular mass/body surface area$^{1.5}$ and did not achieve statistical significance for ventricular mass/height$^{2.7}$. Compared with normal weight subjects, overweight subjects had lower ventricular mass/body weight but higher ventricular mass indexed for height or height$^{2.7}$ in both women and men, as expected from previous results. The left ventricular mass/height$^{2.7}$ was 14% increased in overweight adults (38.6 ± 9.7 vs. 33.8 ± 7.8 g/m$^{2.7}$ in normal weight subjects, $p < 0.001$), consistent with the 14% difference between observed values of ventricular mass and values predicted by using theoretical body surface areas obtained from Metropolitan Life Insurance ideal body weight. In contrast, the difference between overweight and normal weight adults in ventricular mass/height (9% or 90.1 ± 20.8 vs. 82.3 ± 19.8 g/m, $p < 0.01$) was smaller than that observed with indexing for height$^{2.7}$.

Confidence limits of the relation of left ventricular mass to body height. The confidence limits for the relations of left ventricular mass to height are given in Figure 4, A and B for nonobese female and male subjects, respectively. These nomograms are applicable to normotensive subjects 4 months to 75 years old.

Table 4. Ideal Weight and Ideal Body Surface Area for Height in Adults Based on 1980 Metropolitan Life Insurance Tables

Men			Women		
Observed Height (m)	Ideal Body Weight (kg)	Ideal Body Surface Area (m²)	Observed Height (m)	Ideal Body Weight (kg)	Ideal Body Surface Area (m²)
1.54	60.78	1.59	1.43	50.35	1.39
1.55	61.01	1.60	1.44	51.26	1.41
1.56	61.01	1.60	1.47	52.16	1.44
1.59	61.69	1.63	1.50	53.07	1.47
1.60	62.60	1.65	1.51	53.07	1.47
1.61	62.60	1.66	1.52	54.21	1.50
1.62	63.50	1.67	1.54	55.34	1.53
1.63	63.50	1.68	1.55	55.34	1.54
1.65	64.64	1.71	1.56	55.34	1.54
1.66	64.64	1.72	1.57	56.70	1.56
1.67	65.77	1.74	1.58	56.70	1.57
1.68	65.77	1.75	1.59	58.06	1.59
1.69	65.77	1.75	1.60	58.06	1.60
1.70	67.13	1.78	1.61	58.06	1.61
1.71	67.13	1.78	1.62	59.42	1.63
1.72	68.49	1.81	1.63	59.42	1.64
1.73	68.49	1.82	1.64	60.78	1.66
1.75	69.85	1.85	1.65	60.78	1.67
1.76	69.85	1.85	1.66	60.78	1.68
1.77	71.22	1.88	1.68	62.14	1.71
1.78	71.22	1.88	1.69	62.14	1.71
1.79	71.22	1.89	1.70	63.50	1.74
1.80	72.58	1.92	1.72	64.86	1.77
1.82	72.58	1.93	1.73	64.86	1.77
1.83	74.16	1.96	1.75	66.23	1.81
1.84	74.16	1.96	1.76	66.23	1.81
1.85	75.75	1.99	1.77	67.59	1.83
1.89	77.57	2.04			
1.91	79.15	2.07			
1.93	81.19	2.11			
1.96	83.24	2.16			
2.00	87.54	2.24			

In Figure 5, the proportion of subjects whose values for left ventricular mass/height and left ventricular mass/height$^{2.7}$ were in the highest decile of the total group is plotted for the quartiles of height in both children and adults. The progressive increase in the proportion of subjects with relatively higher values of left ventricular mass/height from the lowest to the highest quartile of body height in both children and adults illustrates the systematic error introduced by applying a single mass/height partition value in subjects of different body size. Using height to the 2.7 power eliminated this effect of body height in adults but revealed a concentration of the highest values in the shortest (and youngest) quartile of children. Use of the 95% confidence intervals for ventricular mass/height$^{2.7}$ for the different age strata illustrated in Figure 6 or the nomograms in Figure 4 allows recognition of ventricular hypertrophy without this age effect.

Table 5. Observed and Theoretic Measures of Body Size and Left Ventricular Mass in Normal Weight and Overweight Adults*

	Normal Weight (n = 228)	Overweight (n = 56)	p Value
Age (yr)	38 ± 14	44 ± 12	<0.006
Gender (male/female)	137/91	20/36	<0.001
Body height (m)	1.69 ± 0.10	1.66 ± 0.11	<0.01
Observed body weight (kg)	65 ± 12	83 ± 15	<0.00001
Ideal body weight (kg)	65 ± 7	62 ± 7	<0.005
Body surface area (m^2)	1.74 ± 0.20	1.91 ± 0.22	<0.00001
Ideal body surface area (m^2)	1.75 ± 0.15	1.69 ± 0.16	<0.01
LV mass (g)	140 ± 37	149 ± 36	NS
Ideal LV mass (g)	135 ± 17	128 ± 18	<0.01
LV mass/ideal body weight (g/kg)	2.14 ± 0.48	2.39 ± 0.55	<0.001
LV mass/BSA (g/m^2)	80 ± 18	88 ± 20	<0.002

*Left ventricular mass calculated from American Society of Echocardiography measurements. BSA = body surface area; LV = left ventricular.

Discussion

On the basis of the observation that body proportions differ among organisms of different body size, it has been found useful to use equations to describe the biologic relations between the size of different body components. The relations between the growth of a body part and that of the organism are generally curvilinear or logarithmic. These growth relations are best expressed mathematically by means of allometric equations in which:

$$\text{Size of a body part} = \text{Constant} \times \text{Body size}^{\text{allometric exponent}}$$

Because allometric equations correctly describe relations between organs and body growth and may reveal relations that otherwise remain obscure, their utility for comparisons between individuals or species of different size and for predicting the expected size of organs for a given body size is widely accepted (16,31). We used this approach to test the assumption that left ventricular mass increases linearly with the first power of the three most frequently used variables of body size. The study was performed in three separate groups that were from different geographic areas (U.S. East Coast and Midwest and southern Italy) and differed in ethnic, social and environmental characteristics as well as in the more rigorous exclusion of subjects with established cardiovascular risk factors from the Naples normal-weight group. Despite these differences, the relations of left ventricular mass to the three measures of body size (height, weight and body surface area) across a wide range of age and body size were similar in all groups of normotensive subjects with normal body weight (Fig. 1). Black subjects were well represented in the groups from New York (36%) and Cincinnati (27%); however, the number of black men and women in separate normal weight and overweight strata was too small to permit complete race-specific analyses.

Relation of left ventricular mass to body size. In this study, only the relation of left ventricular mass to body weight approached a power of 1, whereas relations of ventricular mass to both body surface area and body height were substantially different, approximating a power of 1.5 for body surface area and approaching a power of 3 for height. The differences in power of the relations between ventricular mass and the three measures of body size reflect the mathematic relations between variables having different dimensions (22). Thus, left ventricular mass and body weight are three-dimensional measurements, yielding therefore a first-power relation; comparison of ventricular mass with a two-dimensional (body surface area) or a one-dimensional (height) measurement yielded relations to correspondingly higher powers. This result extends the previous observations of Gutgesell et al. (34). They found that in 145 children and adolescents aged 1 day to 19 years old, left ventricular diastolic dimension was more closely related to the cube root of body weight (r = 0.93) than to its absolute value (r = 0.85) and to the square root of body surface area (r = 0.95) than to its absolute value (r = 0.92), whereas the differences between relations with body height and its transformations were minimal (that is, r = 0.92 vs. 0.93 for absolute and square or cube root value, respectively). More recently, Gutgesell and Rembold (35) demonstrated that left ventricular end-diastolic volume (a three-dimensional measure similar to ventricular mass) was related to body surface area to a power of 1.5, a value identical to that found for the relation

Table 6. Impact of Overweight on Left Ventricular Mass* Normalized by Various Measures of Body Size in Adults

	Men		Women		p Value	
	Normal (n = 137)	Obese (n = 20)	Normal (n = 91)	Obese (n = 36)	Gender	BMI
Age (yr)	39 ± 14	44 ± 13	37 ± 15	44 ± 12	NS	<0.004
LV mass (g)	155 ± 34	163 ± 36	117 ± 28	142 ± 35	<0.00001	<0.0003
LV mass/BSA (g/m^2)	85 ± 16	79 ± 19	73 ± 16	78 ± 19	<0.00001†	NS
LV mass/BW (g/kg)	2.2 ± 0.4	1.8 ± 0.5	2.0 ± 0.5	1.8 ± 0.5	<0.001	<0.00001
LV mass/height (g/m)	89 ± 19	93 ± 21	72 ± 17	88 ± 21	<0.00001†	<0.0001
LV mass/$BSA^{1.5}$ (g/$m^{1.5}$)	63 ± 12	56 ± 14	58 ± 13	58 ± 15	<0.01	NS
LV mass/$height^{2.7}$ (g/$m^{2.7}$)	35 ± 8	37 ± 9	32 ± 8	40 ± 10	NS‡	<0.00001

*Left ventricular mass calculated from American Society of Echocardiography measurements. †$p < 0.05$; ‡$p < 0.01$ (gender-specificity of the difference from values in normal weight subjects). BMI = body mass index; BSA = body surface area; BW = body weight; LV = left ventricular.

JACC Vol. 20, No. 5
November 1, 1992:1251–60

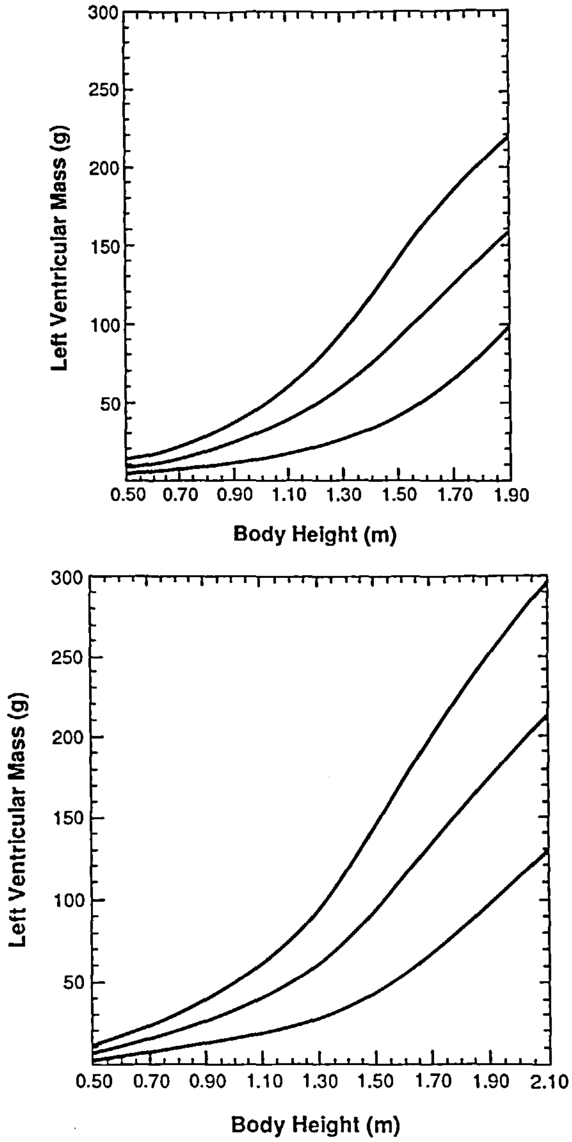

Figure 4. Top, Relation between left ventricular mass and body height in normal weight female infants, children and adults aged 4 months to 75 years. Allometric regression line **(middle line)** and upper and lower 95% confidence limits of this relation are displayed. **Bottom,** Allometric regression line **(middle line)** and upper and lower 95% confidence limits of the relation between left ventricular mass and body height in male infants, children and adults aged 4 months to 75 years.

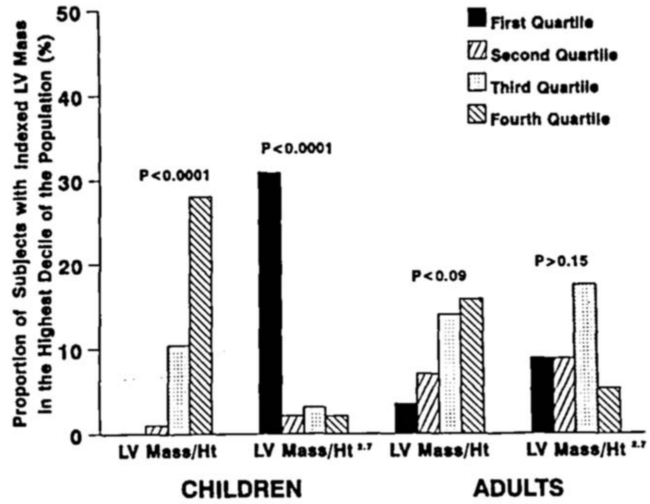

Figure 5. Proportion of subjects with values of left ventricular (LV) mass indexed by height (Ht) or height$^{2.7}$ in the upper decile of the population **(vertical axis)** in relation to quartiles of height **(horizontal axis)**. p values were obtained from chi-square statistics.

between ventricular mass and body surface area in our study group.

Effect of indexing on detection of left ventricular hypertrophy. The use of one normalization instead of another is likely to affect the results when subjects of different body size are compared. For example, Garavaglia et al. (36) recently compared two groups of obese adults with a group of nonobese hypertensive patients. Normalization of ventricular mass for body surface area yielded a significant difference between nonobese and both mildly obese and moderately obese patients (both $p < 0.001$), with a 23% mean increase in ventricular mass index in those with mild obesity. Had height been used to normalize ventricular mass, the mean difference would have been 34%, whereas the mean difference in ventricular mass/body weight would have been only 7%. The intergroup difference would have been 27% with indexing for the 2.7 power of height. The ability to detect left ventricular hypertrophy in obese patients therefore depends on both the measure of body size chosen to index ventricular mass and the choice of simple linear correction or normalization by the power revealed by allometric equations. Preliminary analysis in hypertensive patients has shown that use of the allometric signal for height detects a higher prevalence of left ventricular hypertrophy in overweight patients than does conventional indexing by body surface area (37).

More important, the positive residual relation between left ventricle mass/height and height indicates that larger and implicity prognostically more adverse values for ventricular mass would be found in taller subjects (Fig. 5). However, two large prospective studies have shown that the risk of myocardial infarction in men is inversely related to height (38,39). Normalization of left ventricular mass for height$^{2.7}$ resulted in a weakly inverse residual relation with height that would avoid misleading predictions.

Obesity as a signal for increased left ventricular mass. Longitudinal studies have shown that obesity is a risk factor for cardiovascular diseases (40,41). Cross-sectional studies are inconsistent in reporting higher, lower or similar left ventricular mass/body surface area in normotensive obese compared with normal weight adults, whereas ventricular mass index has been more consistently found to be higher in obese than in normal weight hypertensive adults (20,23, 36,42). The present data further clarify the relation of obesity to ventricular mass; body weight was approximately 28%

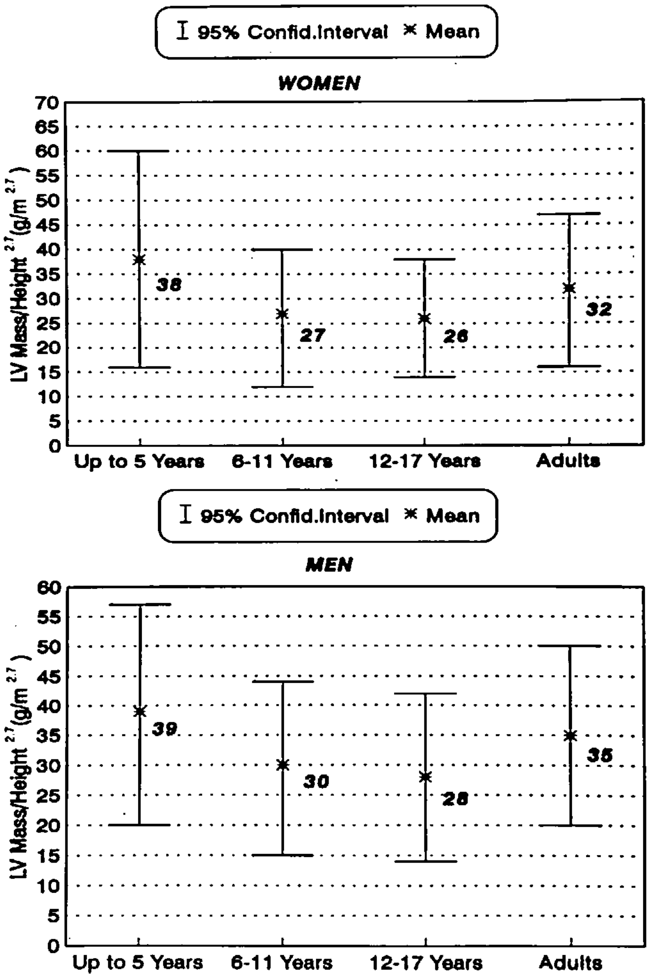

Figure 6. Mean value and 95% confidence (Confid.) interval for left ventricular (LV) mass/height$^{2.7}$ **(vertical axis)** in female **(upper panel)** and male **(lower panel)** subjects in four age groups.

higher in the overweight than in the normal weight adults, but left ventricular mass in the former group was only 14% higher than predicted from ideal body weight. This caused ventricular mass/body weight to be approximately 11% lower in overweight than in normal weight subjects ($p < 0.0001$, Table 6), a finding that is a pronounced deviation from the expected first-power relation between left ventricular mass and body weight (22). The reasons for the diminished allometric signal to increase in ventricular mass provided by excess body weight in adults are uncertain but may include a lower ratio between lean and fat body mass and lower metabolic demand of adipose tissue.

Conclusions. The relations of left ventricular mass to body size are affected by differences in geometric dimensions. Accordingly, the normalization of ventricular mass for measures of body size should take into account the relations among body size measures with different dimensions. Among the indexes studied, both body height$^{2.7}$ and ideal body surface area$^{1.5}$ (generated from ideal body weight for height in Table 4) provide methods of normalizing ventricular mass for body size that reduce its variability among normal weight subjects and correctly detect differences in left ventricular mass between normal and overweight subjects. Nomograms depicting the confidence limits of normal relations between left ventricular mass and body height (Fig. 4) may be used clinically to determine whether a given patient has hypertrophy, independent of the presence of obesity. Indexing for body surface area$^{1.5}$ or body weight reduces ventricular mass variability in normal weight subjects but does not correctly detect left ventricular mass differences related to obesity. Indexing of ventricular mass for height is less successful in reducing variability of ventricular mass among normal weight children or adults, underestimates the increase in mass owing to overweight in adults and results in increases of indexed ventricular mass with greater height ($r = 0.71$ in children and 0.41 in adults in the present study). As more data relating left ventricular mass to prognosis are obtained, it will be important to determine whether indexing left ventricular mass by measures of body size to the allometrically correct power will improve the already strong ability of left ventricular mass indexed by body surface area (1,2) or height (3,4) to predict adverse events.

We thank Daniel Levy, MD, for critical reading of this manuscript and Virginia Burns for assistance in its preparation.

References

1. Casale PN, Devereux RB, Milner M, et al. Value of echocardiographic measurement of left ventricular mass in predicting cardiovascular morbid events in hypertensive men. Ann Intern Med 1986;105:173–8.
2. Koren MJ, Devereux RB, Casale PN, Savage DD, Laragh JH. Relation of left ventricular mass and geometry to morbidity and mortality in men and women with essential hypertension. Ann Intern Med 1991;114:345–52.
3. Levy D, Garrison RJ, Savage DD, Kannel WB, Castelli WP. Left ventricular mass and incidence of coronary heart disease in an elderly cohort. Ann Intern Med 1989;110:101–7.
4. Levy D, Garrison RJ, Savage DD, Kannel WB, Castelli WP. Prognostic implications of echocardiographically determined left ventricular mass in the Framingham Heart Study. N Engl J Med 1990;322:1561–6.
5. Silberberg JS, Barre PE, Pritchard SS, Sniderman AD. Impact of left ventricular hypertrophy on survival in end-stage renal disease. Kidney Int 1989;36:286–90.
6. Cooper RS, Simmons BE, Castaner A, Santhanam V, Ghali J, Mar M. Left ventricular hypertrophy is associated with worse survival independent of ventricular function and number of coronary arteries severely narrowed. Am J Cardiol 1990;65:441–5.
7. Levy D, Labib SB, Anderson KM, Christiansen JC, Kannel WB, Castelli WP. Determinants of sensitivity and specificity of electrocardiographic criteria for left ventricular hypertrophy. Circulation 1990;81:815–20.
8. Devereux RB, Lutas EM, Casale PN, et al. Standardization of M-mode echocardiographic left ventricular anatomic measurements. J Am Coll Cardiol 1984;4:1222–30.
9. Levy D, Savage DD, Garrison RJ, Anderson KM, Kannel WB, Castelli WP. Echocardiographic criteria for left ventricular hypertrophy: the Framingham study. Am J Cardiol 1987;59:956–60.
10. de Simone G, Di Lorenzo L, Moccia M, Buonissimo S, Costantino G, de Divitiis O. Hemodynamic hypertrophied left ventricular patterns in systemic hypertension. Am J Cardiol 1987;60:1317–21.
11. Ganau A, Devereux RB, Atlas SA, et al. Plasma atrial natriuretic factor in essential hypertension: relation to cardiac size, function, and systemic hemodynamics. J Am Coll Cardiol 1989;14:715–24.

12. Mahoney LT, Schieken RM, Clarke WR, Lauer RM. Left ventricular mass and exercise responses predict future blood pressure. The Muscatine Study. Hypertension 1988;12:206–13.
13. de Simone G, Devereux RB, Roman MJ, Schlussel, Alderman MH, Laragh JH. Echocardiographic left ventricular mass and electrolyte intake predict subsequent arterial hypertension in initially normotensive adults. Ann Intern Med 1991;114:202–9.
14. Smith HL. The relation of the weight of the heart to the weight of the body and of the weight of the heart to age. Am Heart J 1928;4:79–93.
15. Stahl WR. Organ weights in primates and other mammals. Science 1965;150:1039–42.
16. Schmidt-Nielsen K. Scaling. Why Is Animal Size So Important? New York: Cambridge University Press, 1984: 1–32, 56–98, 115–64, 209–23.
17. Henry WL, Ware J, Gardin JM, Hepner SJ, McGray J, Weiner M. Echocardiographic measurements in normal subjects. Growth-related changes that occur between infancy and early adulthood. Circulation 1978;57:278–85.
18. Hammond IW, Devereux RB, Alderman MH, et al. The prevalance and correlates of echocardiographic left ventricular hypertrophy among employed patients with uncomplicated hypertension. J Am Coll Cardiol 1986;7:639–50.
19. Daniels SR, Meyer RA, Liang Y, Bove KE. Echocardiographically determined left ventricular mass index in normal children, adolescents and young adults. Am Coll Cardiol 1988;12:703–8.
20. Hammond IW, Devereux RB, Alderman MH, Laragh JH. Relation of blood pressure and body build to left ventricular mass in normotensive and hypertensive employed adults. J Am Coll Cardiol 1988;12:996–1004.
21. de Simone G, Moccia D, Buonissimo S, Di Lorenzo L, Costantino G, de Divitiis O. Normal left ventricle. Quantitative analysis of physical and functional determinants of geometry and performance. Am J Noninvasive Cardiol 1988;2:217–23.
22. McMahon T. Size and shape in biology. Science 1973;179:1201–4.
23. Levy D, Anderson KM, Savage DD, Kannel WB, Christiansen JC, Castelli WP. Echocardiographically detected left ventricular hypertrophy: prevalence and risk factors. The Framingham Heart study. Ann Intern Med 1988;108:7–13.
24. National Institute of Health Consensus Development Panel on the Health Implications of Obesity. Health Implications of Obesity. Ann Intern Med 1985;103:1073–7.
25. Wallerson DC, Devereux RB. Reproducibility of echocardiographic left ventricular measurements. Hypertension 1987;9(suppl II):6–18.
26. Hamill PVV, Drizd TA, Johnson CL, Reed RB, Roche AF, Moore WM. Physical growth: National Center for Health Statistics percentiles. Am J Clin Nutr 1979;32:607–29.
27. Sahn DJ, DeMaria A, Kisslo J, Weyman A.—The Committee on M-mode Standardization of the American Society of Echocardiography. Recommendations regarding quantitation in M-mode echocardiography: results of a survey of echocardiographic measurements. Circulation 1978;58: 1072–83.
28. Devereux RB, Reichek N. Echocardiographic determination of left ventricular mass in man. Anatomic validation of the method. Circulation 1977;55:613–8.
29. Devereux RB, Alonso DR, Lutas EM, et al. Echocardiographic assessment of left ventricular hypertrophy: comparison to necropsy findings. Am J Cardiol 1986;57:450–8.
30. Dubois D, Dubois EF. A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 1916;17:863–71.
31. Zar JH. Calculation and miscalculation of the allometric equation as a model in biological data. BioScience 1968;18:1118–20.
32. Zar JH. Biostatistical Analysis. Englewood Cliffs, NJ: Prentice Hall, 1984:125–6.
33. Metropolitan Life Insurance Company: 1979 Body Build Study. New York: Society of Actuaries and Association of Life Insurance Medical Directors of America, 1980.
34. Gutgesell HP, Paquet M, Duff DF, McNamara DG. Evaluation of left ventricular size and function by echocardiography. Results in normal children. Circulation 1977;56:457–62.
35. Gutgesell HP, Rembold CM. Growth of the human heart relative to body surface area. Am J Cardiol 1990;65:662–8.
36. Garavaglia GE, Messerli FH, Nunez BD, Schmieder RE, Grossman E. Myocardial contractility and left ventricular function in obese patients with essential hypertension. Am J Cardiol 1988;62:594–7.
37. de Simone G, Devereux RB, Roman MJ, Alderman MH, Laragh JH. Obesity increases the prevalence of left ventricular hypertrophy in arterial hypertension (abstr). Am J Hypertens 1991;4:51A.
38. Hebert PR, Rich-Edwards JW, Hanson JE, Ridker PM, Buring JE, Hennekens CH. Height and risk of future myocardial infarction (abstr). Circulation 1991;84(suppl):II–35.
39. Yarnell JWG, Limb ES, Elwood PC, Bainton D. Height: a risk factor for ischaemic heart disease: prospective results from Caerphilly and Speedwell (abstr). Eur Heart J 1991;12(suppl):33.
40. Hubert HB, Feinleib M, McNamara PM, Castelli WP. Obesity as an independent risk factor for cardiovascular diseases: a 26-year of follow-up of participants in the Framingham Heart Study. Circulation 1983;67:968–77.
41. Lew EA. Mortality and weight: insured lives and the American Cancer Society studies. Ann Intern Med 1985;103:1024–9.
42. Messerli FH, Sundgaard-Riise K, Reisin ED, et al. Dimorphic cardiac adaptation to obesity and arterial hypertension. Ann Intern Med 1983;99: 757–61.