INTRODUCTION

Body size is a basic biologic characteristic. It enters into evaluation of health status, disease, and malnutrition, as well as consideration of drug dosage and recommendations for healthy body weight. Height (or stature) is, in a sense, the primary estimate of "size"; it is a determinant of body mass index (most commonly computed as weight/height^2) and is a component in the equations used to compute body surface area. Body mass index and body surface area are, in turn, used as reference bases for interpreting physiologic and clinical tests such as tests of pulmonary and renal function. The rate of increase in height from birth to early adult life has been well studied, and it is recognized to be an essential index of the developmental phase of life. The rate of decrease in height at the end of growth and development has been less thoroughly studied. Indeed, to our knowledge there has been no comprehensive attempt to summarize the literature that is available. However, in recent years there has been increasing interest in the need for age-specific body weight recommendations (1) and in the role of osteoporosis in height loss with aging, making a review of height change timely.

Aside from the purely intellectual interest in the rate at which height changes with aging, the question has practical implications. A number of studies suggest that the body mass index associated with minimal mortality increases with age. In order to determine whether the increase in body mass index-associated minimal mortality is an "artifact" of loss of height with aging, it is necessary to know the magnitude of the artifact. We use the data summarized in this review to quantify the effect of height loss on body mass index independent of any change in weight. To the best of our knowledge, this question has not been previously explored.

It has been recognized that older persons are shorter than middle-aged and young adults, and there have been numerous cross-sectional reports of height differences with age (e.g., see Büchi (2)). However, these studies may not reflect actual height changes as determined longitudinally, that is, by quantifying heights in individuals as they age. "Secular" effects on height—effects due to differences in such environmental variables as quantitative and qualitative nutritional characteristics, prevalence of diseases and activity levels in infancy and childhood, and maternal health and nutrition—have been noted (3, 4). The present report considers all identifiable studies that assessed longitudinal change in height in adults.

Review of the Literature

Search strategy and criteria for acceptability

Studies of longitudinal change in height in adults were identified through a MEDLINE® search using the keywords "human," "height," "stature," and "longitudinal." We searched the MEDLINE® database from 1966 through 1996. To meet our acceptability criteria, studies had to provide data on rates of change in height or data from which the rates of change could be computed within clearly defined age groups, and the published reports had to include a clear presentation of the numbers of subjects in each age category and the duration of the follow-up period. Two reports (5, 6) failed to meet these minimal criteria but are briefly noted here because they had interesting features. Sixteen reports met the criteria; one of them (7) presented data on two separate populations in Wales. Thus, 17 populations were included in this review.

The reliability of estimates of rates of change in height depends on a number of factors: the number of subjects, the number of measurements made per individual, and the length of the follow-up period. Information on these factors is presented below. What cannot be reported are details on methodologic tech-
Methods used to compute rates of height loss

Several methods can be used to compute the rate at which height is lost in different age groups. The simplest and most common method is to measure each subject's height at the beginning and end of the study and divide each subject's height change by the length of follow-up. Subjects are next assigned to age groups based on their age at study entry. The rate (and standard error) of height change for each age group is calculated as the mean (and standard error) of the subject-specific rates for the subjects constituting the group. This method was used in studies I, II, VI, VIII, IX, X, and XIII below. A slight modification of the method, sometimes referred to as a two-stage random effects model, can be used when three or more height measurements are obtained. The method differs from that described above only in that the rate at which height is lost for each subject is calculated by regressing each subject's height on his or her age rather than computing the rate as the difference between the final and initial heights divided by the length of follow-up. This method was used in studies XI, XII, XV, and XVI below. Some variant of the two-stage random effects procedure may have been used in study XIV, as is explained below. For four studies, III, IV, V, and VII, rather than computing the average of subject-specific rates of height change, the rate of height change was computed as the difference between the mean heights of the subjects at the beginning and end of follow-up.

STATISTICAL METHODS

Combining estimates from several studies to derive a consensus equation giving the rate at which height is lost at different ages

A consensus equation which summarizes the rate at which height is lost as a function of age was obtained by regressing the age-specific rates of height loss on age. The age-specific rates came from those studies reviewed and deemed to be acceptable. Additionally, only those age-specific estimates that were computed from a group of 10 or more subjects were included in the computation. Separate equations were developed for men and women. A random coefficients model with an unstructured covariance matrix was used to account for the fact that the slope estimates come from different studies. The model was implemented with PROC MIXED in SAS, version 6.12 (8). As implemented, the model allows each study to have its own intercept and slope (referred to as random effects). The slope and intercept of the consensus equation (referred to as fixed effects) are the means of the study-specific slopes and intercepts. Conceptually, the model is very similar to the two-stage random effects model described above. The unstructured covariance matrix used in our random coefficients model indicates that we make no assumption about the correlation between the slope or intercept estimates from the different studies. Further discussion of random effects models, random coefficients models, and covariance structures can be found in the statistical literature (9).

Computation of cumulative change in body mass index

The cumulative change in height from age \( t \) to age \( 2 \) was obtained by evaluating the definite integral of the consensus equation between the two ages. The cumulative change in height was then used to compute the cumulative change in body mass index from age \( t \) to age \( 2 \), as follows:

\[
\text{Cumulative change in body mass index} = \frac{\text{initial weight}}{(\text{initial height} + \text{cumulative height change})^2} - \text{initial body mass index}.
\]

SUMMARY OF ACCEPTABLE STUDIES

I. Toggenburg, Switzerland (1950)

Büchi (2) reported data on longitudinal change in height for 127 men and 66 women in Toggenburg, Switzerland. The subjects had their height measured at the beginning and end of a 9-year period. Büchi reported sex-specific rates of change in height for six 9-year age groups from age 20–28 years through age \( \geq 65 \) years. For each of the age groups, Büchi presented the number of subjects in the group, the slope, the standard error of the slope, and the statistical sig-
nificance of the slope. In both men and women, there was a significant increase in height in the group aged 20–28 years. Height loss began with the group aged 38–46 years, and the rate of loss increased with age. The rate of height loss was statistically significant beyond age 47. At all ages, women lost height faster than did men, but none of the sex differences were statistically significant.

II. South Wales populations (1967)

Miall et al. (7) studied longitudinal change in height among men and women from two towns in South Wales: Rhondda Fach (follow-up of 6 years) and the Vale of Glamorgan (follow-up of 8 years). In addition to a random sample of the communities, study subjects included as many of their first-degree relatives over 5 years of age as possible, if they lived within approximately 25 miles (40 km). The rate of height change was reported by decade of life from age 25–34 years to age 75–84 years. Data were reported separately for men and women. For each age group, Miall et al. presented the number of subjects in the group and the rate of change in height. Neither the standard error of the slope nor the statistical significance of the slope was presented. The rate of height loss increased with age in both communities. In Rhondda Fach, there was no consistent sex difference in the rates of height loss; in the Vale of Glamorgan, women of all ages lost height faster than did men. The change in height was generally more negative in Rhondda Fach than in the Vale of Glamorgan in both men and women. The authors stated:

The differences between the men in the Vale and the Rhondda may be caused by dissimilar occupations. Many men in the Vale were agricultural labourers, whereas in the Rhondda many were coal miners whose work involved much stooping. However, similar but less pronounced differences were found between females in the two areas, suggesting that some other factor, possibly nutritional, may also play a role in determining this pattern (7, p. 451).

III. Belgian university employees (1967)

Susanne (10) studied the loss of height that occurred over a 22-year period in 41 male staff members of the Institut Royal des Sciences naturelles de Belgique. At study entry, the men were 20–44 years old. The subjects had their height measured twice, once at the beginning of the study and once at the end. We computed the rate at which height was lost in two age groups, 20–32 years and 33–44 years. We computed the mean slopes, their standard errors, and statistical significance by averaging the subject-specific slopes plotted by the authors. The rate of height loss was statistically significantly greater in the older men than in the younger men ($p < 0.01$).

IV. Czechoslovakian men (1971)

Párižková and Eiselt (11) reported the change in height among 55 relatively healthy and fit men in the seventh and eighth decades of life who were followed for a period of 8–10 years. The subjects studied included a group of 24 physically active men and a group of 31 sedentary men. The authors presented the mean heights at the beginning and end of the study by age group within activity status. The subject’s activity status had only a small and probably statistically nonsignificant effect on the rate of height loss, and therefore we combined these two groups by computing a weighted average of the heights. Assuming that the mean duration of follow-up was 9 years, we calculated the number of subjects in each of the two decades of life. Additionally, we computed the rate of height change for the age decades by dividing the difference between the mean heights of the subjects at the beginning and end of the study by 9. Because individual rates of change in height were not presented in the paper, we were unable to compute the standard error of the rate of change in height. The rate of height loss increased with age in this study.

V. Framingham Heart Study (1974)

Gordon and Shurtleff (12) reported the mean heights of 1,202 men and 1,544 women from the Framingham Heart Study who were followed for 18 years (heights were from Framingham examinations 1 and 10). From the mean heights of age groups, we calculated age-specific rates of height loss as the difference between the mean heights at the beginning and the end of the study divided by 18. Rates of loss could be computed separately for men and women within 5-year age groups from ages 29–34 years, 35–39 years, etc., to age 60–62 years. The number of subjects in each age group was given. Because individual rates of height change were not presented, we were unable to compute the standard errors (or the statistical significance) of the rates of height loss. There was an increasing rate of height loss with increasing age in both men and women. Men lost height faster than women in the three youngest age groups; women lost height faster than men in the two oldest age groups. Because the standard errors of the slopes could not be computed from the data presented, it was not possible to determine whether any of these differences were statistically significant.
VI. Norwegian men and women from Finnmark (1976)

Forsdahl and Waaler (13) reported the longitudinal change in height among Norwegian men and women aged 25–84 years at study entry who were followed for 5–6 years (from 1966 to 1971–1972). Sex-specific rates of height change and the numbers of subjects in each group were presented within 5-year age groups from age 24–29 years through age 80–84 years. Neither the standard errors nor the statistical significance of the rates of height change was presented. The rate of height loss increased with age in men and women, but there was no sex difference until age 60–64 years. From age 60–64 years to age 80–84 years, the loss of height was greater in women than in men. Maximum height in men and women occurred at approximately age 26–36 years.

VII. Gothenburg Longitudinal Study (1979)

Steen et al. (14) studied longitudinal height change in a representative sample of 28 men and 37 women from Gothenburg, Sweden, over a 5-year period. At study entry, all subjects were 70 years of age. Mean heights at ages 70 and 75 years were given. From these data we could compute the mean change in height per year (as the difference between height at age 75 minus height at age 70 divided by 5), but neither the standard errors nor the statistical significance of these slopes could be calculated. In this small cohort, the rate of height loss was slightly greater in women than in men.

VIII. Study of Women in Gothenburg (1980)

Noppa et al. (15) reported data obtained from the 6-year follow-up of five birth cohorts of Swedish women ranging in age from 38 years to 60 years when they were studied in 1968–1969. The authors stated, “The method of sampling, together with the high participation rate, ensured that the sample was representative of the general population of women in the ages studied” (15, p. 151). Numbers of subjects and rates of height change, along with the standard error and statistical significance of each rate, were presented for women who were aged 38, 46, 50, 54, and 60 years of age at study entry. Longitudinal loss of height increased progressively with age, except for the oldest age group (aged 60 years at entry), and the loss was statistically significant in the four age groups 46 years–60 years. The youngest age cohort had a trivial and nonsignificant increase in height.

IX. Edinburgh Study (1981)

Milne (16) reported results of a 5-year longitudinal study of height change among 112 men and 141 women aged 62 years and over who resided in Edinburgh, Scotland. Subjects were invited to participate in the study based on the results of a “simple random sample of the 27,000 persons in that age range living in 10 city wards in north Edinburgh” (16, p. 64). Fifty-four percent of the men and women who participated at the beginning of the study were examined 5 years later. Subjects were divided at entry into two age groups, 62–69 years and 70–80 years (perhaps up to age 90). Milne presented age groupings for the subjects who participated in a cross-sectional study. The exact age grouping for the subjects who participated in the longitudinal analysis was not given. For the subjects in the longitudinal analysis, numbers of subjects and rates of height loss, along with their standard errors and statistical significance, were given. There was a significant longitudinal decrease in height in both age groups in men and women. The decrease was greater in the older subjects than in the younger subjects among both men (p < 0.01) and women (p < 0.06). Women lost height more rapidly than men in both age groups, but the difference was statistically significant only in the younger group (age 62–69 years: difference = 0.081 (standard error 0.030), p < 0.01; age 70–90 years: difference = 0.059 (standard error 0.060), p < 0.33).

X. Normative Aging Study (1983)

Borkan et al. (17) studied 1,212 predominantly White middle income men aged 22–82 years at study entry for a period of 8–12 years (mean = 10 years). The rate of height change was presented by age decade from ages 22–29 years, 30–39 years, etc., to age 70–82 years. Although the number of subjects in each age group and the statistical significance of the rate of change in each age group were given, the standard errors of the individual rates of change were not given. An earlier report from this population on 5-year longitudinal change in height was published by Friedlaender et al. (18). The magnitude of the longitudinal change increased with age.

XI. Albuquerque cohort (1988)

Chumlea et al. (19) studied 122 women and 98 men aged 65–84 years at study entry in Albuquerque, New Mexico. The independently living Caucasian subjects in this report were free of major illnesses and were not receiving prescription medications at the start of the study. They were generally well educated and more affluent than the average elderly population. The subjects were studied annually from 1980 through 1986 and had 4–7 height measurements. Sex-specific rates of height change within 5-year age groups (65–69 years through 80–84 years), along with numbers of
subjects, standard errors of rates of height change, and the statistical significance of the rates, were presented. An annual rate of height loss of 0.4-0.6 cm/year was observed in study participants. The rate of height loss did not increase with increasing age, nor did women lose height faster than men. The longitudinal changes reported in this study (19) were very much larger than those reported for other populations (figures 1 and 2).

XII. Tucson Epidemiological Study of Chronic Obstructive Lung Disease (1989)

Cline et al. (20) quantified longitudinal change in height (length of follow-up: mean = 10.5 years; range, 5.0-13.5 years) among persons aged ≥20 years primarily from White, non-Mexican-American households. The subjects were recruited by means of a random cluster sample of households stratified by the age of the head of the household, ethnicity, and socioeconomic status. A total of 751 men and 1,001 women were included; the mean number of height measurements made was 5.7 for men and 5.8 for women.

The authors gave the number of subjects in each birth-year group, as well as the rates of height change and their standard deviations. We calculated the ages of the groups from the birth-year groups, assuming that subject examinations occurred in 1972, on average (the initial examinations were carried out from

**FIGURE 1.** Slopes of height change with age (cm/year) among men from 16 populations. In the Gothenburg population (H), only one age group was studied. A—Toggenburg, Switzerland (2); B—Rhondda Fach, Wales (7); C—Vale of Glamorgan, Wales (7); D—Brussels, Belgium (10); E—Czechoslovakia (11); F—Framingham, Massachusetts (12); G—Finnmark, Norway (13); H—Gothenburg, Sweden (14); J—Edinburgh, Scotland (16); K—Boston, Massachusetts (17); L—Albuquerque, New Mexico (19); M—Tucson, Arizona (20); N—southern Arizona (21); O—Busseton, Australia (22); P—Columbia, Missouri (23); Q—Baltimore, Maryland (24).
February 1972 to April 1973). In addition to these age-specific values, the authors gave slopes from age 25 years to age 85 years (20). These slopes were not age-specific; they were obtained by evaluating an equation giving the sex-specific slope for age in the entire population. The sex-specific equations were obtained by first regressing each individual’s height on age to obtain the subject-specific rate of height loss. The subject-specific slopes were then regressed on age, within-sex, to obtain the relation between slope and age. The two equations that resulted from this last step, one for men and one for women, were then used to obtain the smoothed slopes that were presented by the authors. These “smoothed” data were not included in our computation of the consensus rate of height change; instead, we used the values obtained from the birth-group-specific data presented by the authors.

The study found an increasingly rapid rate of height loss with increasing age. Women lost height faster than did men from age 38 years onward, but the differences were very small until age ≥68 years.

XIII. Southern Arizona communities (1990)

Galloway et al. (21) studied change in height and bone mineral status among community-dwelling Caucasians (90 men and 237 women) from three communities in southern Arizona. The subjects were fol-
employed to compute the coefficients, but we are not in each age group. The rates of height change we values of the slopes, or the number of subjects the repeated stature measures" (22, p. 434). We assume that presented by the authors, nor were the standard errors, the rates of height change, the numbers of subjects, the given by the authors. The coefficients presented by the authors came from a "random regression analysis of some variation of a random effects model was given for men aged 55-59 years or 85-89 years.)

The results of this study were not consistent with the results of other studies reviewed (figures 1 and 2). The rates of height loss for the men were all considerably smaller than those of other studies; in women, the slopes for the three age groups from age 60 years to age 74 years were also much smaller than those of other studies.

XIV. Busselton, Australia (1991)

Chandler and Bock (22) studied the rate of longitudinal change in height among 1,544 men and 1,785 women, predominantly of Northern European descent, in a community health survey begun in 1966 in Busselton, Western Australia. To be eligible for the study, subjects had to have their height measured at least three times at 3-year intervals between 1966 and 1981. The mean number of height measurements was 4.4 for men and 4.6 for women (range, 3–6). The mean duration of follow-up was 10.8 years for men and 10.2 years for women. Upon entry into the study, the men were aged 18–94 years and the women were aged 18–97 years.

We computed rates of height change for seven age decades—20–29 years, 30–39 years, ..., ≥80 years—from the sex-specific coefficients given by Chandler and Block for the quadratic equations relating height to age in the entire population. The computation involved finding the first derivative of the equation relating height to age and evaluating the derivative at the ages given by the authors. The coefficients presented by the authors came from a "random regression analysis of repeated stature measures" (22, p. 434). We assume that some variation of a random effects model was employed to compute the coefficients, but we are not certain. The analytic strategy was not further described.

Age-specific rates of height change were not presented by the authors, nor were the standard errors, the p values of the slopes, or the number of subjects in each age group. The rates of height change we computed may be considered to be smoothed estimates from the entire longitudinal experience in Busselton.

The slopes for both men and women became more negative with increasing age. Beyond age 45 years, the rate of height loss was greater for women than for men. The study demonstrated a curvilinear cross-sectional relation between height and age.

XV. University of Missouri (1992)

Flynn et al. (23) reported results of a 20-year longitudinal study of 144 male members of the faculty and staff of the University of Missouri. Most of the volunteers were college-educated, physically active, and in apparent good health. Their ages at enrollment in 1969–1976 ranged from 32 years to 71 years. Heights were measured three times over a period of 20 years. The rates of change in height, along with numbers of subjects and the statistical significance of the rates of height loss, were presented for five 8-year age groups ranging from 32–39 years through 64–71 years.

The rates of height loss for the four age groups from 32–39 years to 56–63 years were much larger than those from any other of the studies at these ages (figures 1 and 2). The reason for the remarkably greater rate of height loss reported is not clear. The expected increase in the rate of loss with age was evident, however.

XVI. Baltimore Longitudinal Study of Aging (1999)

Sorkin et al. (24) studied longitudinal height data obtained from 1,068 men followed for 15.4 years (standard deviation 8.8) and 390 women followed for 9.0 years (standard deviation 3.6) in Baltimore, Maryland. Subjects were community-dwelling, generally middle and upper middle class, highly educated Caucasian volunteers enrolled in a long term study of aging who were aged 20–94 years at entry. The subjects in this study had their height measured multiple times; the mean number of height measurements was nine for men and five for women. Sex-specific rates of height loss were presented for nine decades of life: 17–19 years, 20–29 years, 30–39 years, ..., 80–89 years, and 90–94 years. Along with the rate of height change for each age group, the number of subjects, the standard error of the slope, and the significance of the slope were presented. The rate of height loss increased monotonically with increasing age. Women in this study lost height more rapidly than did men at all ages.

UNACCEPTABLE STUDIES

Two studies did not meet all of our criteria for acceptability but are of some interest. They are described below.

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Chelsea pensioners (1954)

Lipscomb and Parnell (5) reported height change in a group of retired British military personnel. The data presented in the paper were inadequate for assessment of the rate of longitudinal change in height. The height of 50 pensioners (mean age = 73 years; range, 56–84 years) was compared with the height of only 44 of the men from this group at the time they had “joined the colours” (mean age = 20.5 years; range, 18–26 years). The heights of the missing six men at the time they enlisted were excluded from the analysis because of their age; they had been less than 18 years of age (in fact, one was only 13) when they enlisted and might not yet have achieved their full adult height. The authors suggested that even the 18- to 26-year-old men might not have achieved full adult stature at the time of their initial height measurement 50 years earlier (some of the men enlisted in the Boer War at the turn of the century) (5). Because of these problems, no conclusion can be made about the rate at which height was lost over the 53-year period covered by the study.

Basel Study (1967)

Gsell (6) reported data on longitudinal change in height among 72 men who were either employees of a Swiss pharmaceutical company or their sons. The age distribution given was as follows: 6–24 years, n = 15; 25–39 years, n = 47; and 40–60 years, n = 10. Subjects were examined every 1–2 years over an 8- to 10-year period; the exact number of measurements made was not given. Data on height change were reported not according to the age groupings presented above but rather by age decade. The number of subjects in each age decade was not reported. Despite the limitations of the report, it did show that the rate of height loss increased with age, from −0.06 cm/year in the men aged 30–40 years to −0.14 cm/year in the men aged 40–50 years (6).

Because the Chelsea and Basel studies did not meet our criteria for acceptability, they are not included in the discussion below.

DISCUSSION

Summary of longitudinal studies

This paper summarizes data from 17 populations on the effect of age on longitudinal change in height (table 1). These populations were described in 16 reports; the report by Miall et al. (7) gave data on two South Wales populations. Seven of the populations were from the United States (12, 17, 19–21, 23, 24). Nine of the populations were from Europe: three from the United Kingdom (7, 16), one from Belgium (10), one from Czechoslovakia (11), one from Norway (13), two from Sweden (14, 15), and one from Switzerland (2). One population was from Australia (22). The published data came exclusively from Caucasian populations; we were unable to locate any data on non-Caucasian populations. Among the 17 populations, 16 had data for men (2, 7, 10–14, 16, 17, 19–24) and 13 had data for women (2, 7, 12–16, 19–22, 24). Because the age-specific rates of height loss were unstable when data from a small number of subjects were used to compute the rates, those age groups with less than 10 subjects were included in tabular results that are available upon request but were excluded from both the computations presented below and the figures.

The longitudinal data from three of the 16 populations of men—those from Albuquerque (19), southern Arizona (21), and the University of Missouri (23)—were clearly extreme values that were not consistent with the data from the remaining 13 studies (figure 1). The southern Arizona study (21) found an increase in height among men aged 70–74 years; the Albuquerque study (19) found a loss of height as large as 6 cm per decade. Two of the three studies that had clearly extreme rates of height change in men also had extreme rates of height change in women (the Albuquerque (19) and southern Arizona (21) studies (figure 2); the University of Missouri study (23) did not include women). The reasons for the extreme values in these three studies cannot be determined from the published reports, but small sample size is clearly not the explanation. A number of the studies reporting nonextreme rates of height loss reported age-specific rates of height loss that came from age groups with fewer subjects than those in the studies that reported extreme rates of height loss. The data from the three studies with extreme results will not be considered further in this review. Therefore, the remainder of this paper discusses only 13 populations of men and 11 populations of women. Within these populations, there is quite remarkable consistency by sex in the age-specific rates of height loss. The consistency is even more remarkable when one realizes that the magnitude of the annual rate of height loss is on the order of 0–3 parts per thousand, or tenths of a centimeter lost per year for persons whose original height might have been 170 cm.

A plot of the differences, by age, in the slopes for men and women (figure 3) from the 10 studies that presented age-specific slopes for men and women demonstrates that from age 20 through age 40, there is no pattern in the differences; some studies indicated that men lose height faster, others that women lose height faster. Beyond age 40 years, women lose...
An increase in the rate of height loss with increasing age is evident in all 13 populations of men and all 11 populations of women. Of these 24 populations, 22 had information on age-specific rates of height loss for two or more age groups, and so could be examined to determine whether the rate of height loss increased with age. (The Gothenburg Longitudinal Study (14), which enrolled both men and women, had only one age group, persons aged 70 years.) In all 22 populations, the rate of height loss very consistently increases with age.

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Cumulative loss of height with aging

Three of the studies, the Tucson Epidemiological Study (20), the Busselton, Australia study (22), and the Baltimore Longitudinal Study of Aging (24), computed the cumulative loss of height with age. The data from all of the populations reviewed in this paper can be combined to determine a "consensus" rate at which height is lost at any age (figure 4). The consensus rate of height loss can be used to compute the cumulative loss of height with age (figure 5). The consensus rate of height loss is computed by plotting the value for each of the age-specific slopes (i.e., the rates at which height is lost) at the mean age of each age group and then regressing the slopes on age (figure 4) as described above. Age-specific slopes obtained from groups of less than 10 subjects were excluded both from the plots and from the regressions. For men, the equation relating slope to age was

\[ \text{Slope} = 0.1258 - 0.0041 \text{age}. \]  

(1)
The slope for women was

\[ \text{Slope} = 0.1727 - 0.0054 \text{ age}. \]  \hspace{1cm} (2)

For both men and women, the coefficient of the age term and the intercept were significant at \( p < 0.0001 \). For men, age explained 87 percent of the variation in the rate at which height was lost; in women, age explained 86 percent. The regression lines for men and women (figure 4) indicate that the slope is slightly positive until approximately age 30; that is, height increases slightly. Beyond approximately age 45 years, women lose height faster than do men.

Equations 1 and 2 above give the rate at which height changes at any age. In effect, these equations give the “instantaneous” rate of height loss, \( \frac{d\text{height}}{d\text{age}} \). Because the instantaneous rate of height loss is the first derivative of the equation relating height to age, the equation relating height to age can be obtained by integrating equations 1 and 2 with respect to age. Furthermore, evaluation of the integrals at two ages will give the average cumulative change in height that occurs with aging.

\[
\text{Cumulative height change} = \int \frac{d\text{height}}{d\text{age}} \ d\text{age} = \int \text{slope} \ d\text{age}.
\]

For men, the equation for cumulative loss in height is

\[
\text{Cumulative height change} = \int (0.1258 - 0.0041 \text{ age}) \ d\text{age} = 0.1258 \text{ age} - 0.0021 \text{ age}^2,
\]  \hspace{1cm} (3)

and for women it is

\[
\text{Cumulative height change} = \int (0.1727 - 0.0054 \text{ age}) \ d\text{age} = 0.1727 \text{ age} - 0.0027 \text{ age}^2.
\]  \hspace{1cm} (4)

A plot (figure 5) of equations 3 and 4 indicates that by age 80 years, the average man will have lost approximately 5 cm from his maximum height, the average woman approximately 6.2 cm.

**Effect of loss of height on body mass index**

The cumulative change in height with aging will affect the interpretation of the body mass index at different ages. Body mass index, computed as weight (in kilograms) divided by the square of height (in meters), is often used as an index of obesity. If weight remains constant with aging, the body mass index will increase “artifactually” as height is lost with aging. The magnitude of the artifact can be calculated by substituting for cumulative height change in the equation:

\[
\text{Cumulative change in body mass index} = \frac{\text{initial weight}}{(\text{initial height} + \text{cumulative height change})^2} - \frac{\text{initial weight}}{(\text{initial height})^2}.
\]

In men, the equation for cumulative change in body mass index is

\[
\text{Cumulative change in body mass index} = \frac{\text{initial weight}}{(\text{initial height} + 0.1258 \text{ age} - 0.0021 \text{ age}^2)^2} - \frac{\text{initial weight}}{(\text{initial height})^2},
\]

and in women the equation is

\[
\text{Cumulative change in body mass index} = \frac{\text{initial weight}}{(\text{initial height} + 0.1727 \text{ age} - 0.0027 \text{ age}^2)^2} - \frac{\text{initial weight}}{(\text{initial height})^2}.
\]

Because the cumulative height change beyond age 30 is always negative, i.e., a loss of height, the cumulative effect of height change on body mass index beyond age 30 will be to increase the body mass index. In the average man, the magnitude of the cumulative change in body mass index due solely to loss of height will be an artifactual increase in body mass index of 1.2 units from age 30 to age 80; in the average woman, the artifactual increase will be 1.6 units (figure 6). If the body mass index (kg/m\(^2\)) at age 30 were 22, a 1.6-unit increase in body mass index in a woman will result in a 7 percent “error” in the body mass index at age 80.

Another way of expressing these effects is to compute the weight gain equivalent to the height loss. Since one unit of body mass index is equivalent to 3.2 kg (7 pounds) in a man of average height (1.75 m) and 2.7 kg (6 pounds) in a woman of average height (1.63 m), the 1.2-unit increase in body mass index in...
FIGURE 6. Change in body mass index (BMI) (weight (kg)/height (m)²) due solely to the loss of height with aging (i.e., assuming constant body weight) in men (solid curved line) (2, 7, 10–14, 16, 17, 20, 22, 24) and women (dashed curved line) (2, 7, 12–16, 20, 22, 24), as compared with the change in body mass index recommended by the Gerontology Research Center (GRC) table (25) (solid straight line), the National Research Council (NRC) (26) (dashed straight line), and the 1983 Metropolitan Life Insurance Company table (27) (horizontal dashed line).

TABLE 2. Optimal body mass index* recommendations from several sources compared to change in body mass index due solely to loss of height with aging

<table>
<thead>
<tr>
<th>Source of body mass index recommendations</th>
<th>Recommended body mass index at age:</th>
<th>22 years</th>
<th>30 years</th>
<th>40 years</th>
<th>50 years</th>
<th>60 years</th>
<th>70 years</th>
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</thead>
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<tr>
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<td></td>
<td>20.1</td>
<td>21.3</td>
<td>22.9</td>
<td>24.5</td>
<td>26.1</td>
<td></td>
</tr>
<tr>
<td>National Research Council (26)</td>
<td></td>
<td>21.5</td>
<td>22.5</td>
<td>23.5</td>
<td>24.5</td>
<td>25.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Dietary Guidelines for Americans, 1990</td>
<td></td>
<td>22.0</td>
<td>22.0</td>
<td>24.0</td>
<td>24.0</td>
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<tr>
<td>Dietary Guidelines for Americans, 1995</td>
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<td>22.0</td>
<td>22.4</td>
<td>22.4</td>
<td>22.4</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
<td>1983 Metropolitan Life tables (27)</td>
<td></td>
<td>22.0</td>
<td>22.0</td>
<td>22.0</td>
<td>22.4</td>
<td>22.7</td>
<td>23.0</td>
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</tbody>
</table>

Body mass index change due to height change with age

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<th></th>
<th>22.0</th>
<th>22.0</th>
<th>22.0</th>
<th>22.2</th>
<th>22.4</th>
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<tbody>
<tr>
<td>Men</td>
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<td>Women</td>
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<td>22.0</td>
<td>22.2</td>
<td>22.5</td>
<td>23.0</td>
</tr>
</tbody>
</table>

* Weight (kg)/height (m)².
† The Gerontology Research Center, National Research Council, and Dietary Guidelines for Americans tables are not sex-specific; that is, separate tables for men and women were not deemed to be necessary. For the 1983 Metropolitan Life tables, the body mass indices at the midpoint for the medium frame are essentially the same for men and women at their sex-specific average height; heights were corrected for shoe height (2.54 cm for both men and women), and weights were corrected for weight of clothes (2.3 kg for men, 1.4 kg for women). The body mass indices given in the table (except for the last two lines) represent the midpoints of the recommended ranges from the sources cited.

The change in height with aging has implications beyond the interpretation of body mass index. Weight-for-height guidelines, though sometimes expressed as a series of heights and their corresponding recommended weights rather than as body mass indices, are by their very nature lists of recommended body mass indices. Two sets of weight-for-height guidelines, the Gerontology Research Center table (25) and the recommendations of the National Research Council (26), indicate that minimal mortality occurs at progressively higher body mass indices with increasing age (table 2, figure 6). The Gerontology Research Center table indicates that minimal mortality is associated with a 1.6-unit increase in body mass index per decade of adult life; the National Research Council recommends a 1.0-unit increase in body mass index per decade. It has been suggested that the increase in the body mass index associated with minimal mortality with increasing age could be an artifact of the loss of height with aging. The effect of height loss on body mass index can be seen to be much smaller than the increase in body mass index associated with minimal mortality (table 2, figure 6).
LIMITATIONS OF THIS REVIEW

Implications of the lack of epidemiologic rigor in the results reported

In reporting longitudinal data, it is considered good epidemiologic practice to state the percentage of people lost to follow-up and to try to determine whether nonrandom loss to follow-up could have introduced bias into the results reported. It is also considered advisable to give data establishing the repeatability of the measure of interest and to demonstrate that there was no change in measurement technique during the course of the study—a change that could produce a spurious “longitudinal effect.” Unfortunately, these steps were not taken in this field of study.

None of the studies described in this review compared characteristics of subjects lost to follow-up with those of persons who were seen at the beginning and end of the follow-up period. Furthermore, none of the published articles gave statistics on the repeatability of height measurements for either short term or long term follow-up. The uniform lack of “epidemiologic rigor” in the studies may reflect the fact that height is generally believed to be accurately and reliably measured. The consistency in the reported results among these studies (figures 1 and 2) makes it likely that the effects reported are real and not produced by a change in method. Although most of the studies summarized did not use random samples of the population, the consistency among the results—results that come from many populations and many parts of the world—suggests that they are quite generalizable, at least to Caucasian populations.

Thoughts on combining data from different studies

When estimates from several studies are combined so that a consensus estimate of an effect can be computed, the estimates are often weighted by the inverse of their variance. There are several reasons for weighting: to assign greater weight to estimates in which we have greater confidence (and conversely lesser weight to estimates in which we have lesser confidence), and to stabilize the variance of the resulting consensus estimate. Unfortunately, weighting was not an acceptable option for the data reviewed in this report; too much information would have been eliminated. Only four of 11 studies of women (36 percent) and five of 13 studies of men (38 percent) provided estimates of variance (or the standard error and number of subjects in each age group, which could have been used to compute the variance). Failure to weight estimates can, in theory, affect the consensus estimate of the effect. To estimate the effect that failure to weight might have on the consensus estimates of the rate at which height changes, the cumulative change in height, and the cumulative change in body mass index, we compared the weighted and unweighted estimates of these three metrics from the four studies of women and five studies of men in which the age-specific variances could be computed. The comparison demonstrated that there were no important differences between the weighted and unweighted estimates (data available upon request). It therefore seems likely that the failure to weight when we developed our consensus equations of the rates of change in height among men and women had no substantial effect on the results we reported.

Suggestions for future studies

The age-specific rates of longitudinal loss of height in Caucasian men and women have been well investigated. There is a remarkable consistency in the rate of height loss across studies from widely different geographic locations and ethnic groups (figure 4). Although the cumulative loss of height with aging is large, the effect of the loss on body mass index is modest. Future studies should seek to determine the etiology of the height loss. There is a need to determine rates of longitudinal loss of height in non-Caucasian populations. Among women, loss of bone mineral density is known to increase at the time of menopause. It would be interesting to know whether there is an acceleration in the rate of height loss shortly after the increased rate of demineralization begins.

In all future studies, researchers should strive for greater epidemiologic rigor than has been the norm for studies of the rate of height change with age. As we noted above, the investigators should describe the methods used to standardize the measurement of height and to assure that methodologic drift did not occur over time. An attempt should be made to determine whether differential loss to follow-up could have affected the estimates of rates of height loss. For each age group studied, the number of subjects studied should be given, as well as an estimate of the precision with which the rate of height change has been measured. This estimate could take the form of the standard error, the standard deviation, or the variance of the rate of height change.

REFERENCES

Verlag Ferdinand Berger, 1950.


