Conf-9406107--5

REFERENCE MAN ANATOMICAL MODEL

Mark Cristy

Oak Ridge National Laboratory

Oak Ridge, Tennessee

ABSTRACT

The 70-kg Standard Man or Reference Man has been used in physiological models since at least the 1920s to represent adult males. It came into use in radiation protection in the late 1940s and was developed extensively during the 1950s and used by the International Commission on Radiological Protection (ICRP) in its Publication 2 in 1959. The current Reference Man for Purposes of Radiation Protection is a monumental book published in 1975 by the ICRP as ICRP Publication 23. It has a wealth of information useful for radiation dosimetry, including anatomical and physiological data, gross and elemental composition of the body and organs and tissues of the body. The anatomical data includes specified reference values for an adult male and an adult female. Other reference values are primarily for the adult male. The anatomical data include much data on fetuses and children, although reference values are not established. There is an ICRP task group currently working on revising selected parts of the Reference Man document.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

INTRODUCTION

The 70-kg "standard man" representing a typical Western adult male has been used in physiological models since at least the 1920's. In order to facilitate comparisons of internal radiation dose estimates among health physicists in the U.S., the U.K., and Canada, the standard man concept was adopted at the Chalk River conference in 1949 to represent a typical radiation worker. Additional data necessary for radiation dose calculations in the 70-kg standard man were agreed: masses of 25 organs and tissues; total body content of 15 elements; total water intake and output and content of the body; and some anatomical and physiological data on the respiratory tract (Chalk River Conference, 1950). In its Publication 2 on permissible doses for internal radiation in 1959, the International Commission on Radiological Protection (ICRP) modified and vastly extended the biological data for this 70-kg man: its Table 6 has estimates of the content, in grams and per cent by weight, of 46 elements in the total body; Table 7 has estimates of the content, in μg/g wet weight, of 44 elements in 46 organs and tissues; Table 8 has the mass and effective radius of over 30 organs and tissues; Table 9 has standard values for some intake and excretion parameters for water balance and air balance; Table 10 has standard values for retention of particulates in the respiratory tract; Table 11 has data on the gastrointestinal tract (mass of contents, residence times for food, and soluble and insoluble fractions going from lungs to GI tract); and Table 12 is an enormous table giving for every element from Z=1 to Z=98, wherever data were available, data on average daily ingestion, average concentration in total body or selected reference organs, biological half-life in body or organ, fraction absorbed from GI tract to blood, fraction in organ of reference to that in total body, fraction from blood to organ of reference, and fractions reaching organ of reference by ingestion and by inhalation.

The introduction to ICRP Publication 23 on Reference Man (1975) has additional information on the historical development of the standard man concept in radiation protection during the 1950's. Poston (1983) has also reviewed this subject, including the 1975 Reference Man.

In December 1963 Committee II of the ICRP requested that the Main Commission establish a task group of the revision and extension of the standard man concept. The name was changed later to Reference Man, at the suggestion of the Main Commission, and Reference Man was published in a monumental 480-page book in 1975. The Reference Man book has similar data to that published in Tables 6-12 of ICRP Publication 2, but the sources of the data are documented and the data are updated and extended. Data on women, children, and fètuses were also collected, where available, but these data are primarily anatomical data and fewer reference values are identified for these groups.

A number of persons worked hard on this report, but I want to single out two of them for special recognition, based on what persons close to the work have told me and from my own reading of a file of the correspondence among the task group during its work. Both are from Oak Ridge National Laboratory: the late Walter S. Snyder was the main organizer and task-master, and Mary Jane Cook collected and digested much of the enormous biological data. Her contributions go back at least to 1948, an unpublished "Survey Report of the Characteristics of the Standard Man," i.e., before the Chalk River conference of 1949.

ICRP REFERENCE MAN, 1975

General Purposes for the Reference Man

The purposes for Reference Man are spelled out in the introduction to ICRP Publication 23:

> Estimation of radiation dose to the human body, whether from external or internal sources, requires a certain amount of data about the exposed individual. In the case of external sources, fairly simple specifications of mass, dimensions, and elemental compositions of the organs and tissues concerned are largely sufficient for most situations. However, in order to calculate maximum permissible annual intakes (MPAI) and related secondary standards for radioactive substances, as well as for estimation of dose due to a specified intake of radioactive material entering the body, it is necessary to have much more biological information concerning the individual potentially or actually exposed. Daily intakes of air and water or of elements which serve as carriers and, to some extent, influence the uptake of other elements, the breathing rate, data on excretion, and parameters governing the elimination rates of the material from various tissues or from the body are examples of the wide variety of data that may significantly influence the estimate of dose. Since the uptake and retention in man of many radionuclides cannot be determined accurately, data on the corresponding stable elements are often useful for constructing a retention model and for checking the calculations. Finally, in assessing the exposure of a population, the age dependence of such factors is also necessary.
>
> Although individuals vary considerably in such respects, it is important to have a well-defined reference individual for estimation of radiation dose. Such a reference individual is convenient for routine cases of estimation of dose when the levels are sufficiently low that individual differences may be ignored. Hopefully, such a reference individual will be recognized and used widely so that health physicists can compare and check their results without tedious enumeration of assumptions or without the risk of minor differences in these assumptions obscuring the basic agreement or disagreement of their results. Most important, perhaps, is the consideration that when it is desirable to adjust published results to make a more precise estimate of dose for a given individual, the basis of the published estimates is needed. Therefore, unless the bases for published estimates of doses, or MPAIs or body burden values, given or implicit in ICRP recommendations, are carefully specified, it is difficult to adjust those values to meet the needs of special situations and individuals, and each health physicist must begin *ab initio* in every instance. It is expected that Reference Man as defined here will suffice for most purposes of planning or for exposures at low levels.

Definition of Reference Man

Reference Man is actually a shortened form for "Reference Man for Purposes of Radiation Protection." The Task Group on Reference Man limited "its attention to those characteristics of man which are known to be important or which are likely to be significant for estimation of dose from sources of radiation within or outside the body" (ICRP 23, p. 3). In spite of its (properly) limited purpose, ICRP 23 has been widely used by scientists outside radiation protection, as shown in a citation study I did in 1987 using Science Citation Index.

Reference Man was defined as 20-30 years old, weighing 70 kg, 170 cm in height, and living in a climate with an average temperature of from 10° to 20° C (the specification of climate is important in water balance). He is a Caucasian and is a Western European or North American in habitat and custom. Reference Woman is 60 kg and 160 cm in height, but she was not defined in as much detail as Reference Man, especially in terms of chemical composition of the body, largely for lack of data.

Organization of ICRP Publication 23

The Reference Man book comprises three chapters: (1) Anatomical Values for Reference Man, (2) Gross and Elemental Content of Reference Man, and (3) Physiological Data for Reference Man. It should be mentioned that work on respiratory tract and gastrointestinal tract models for dosimetry were done separately and published in companion papers in *Health Physics* in 1966 (Task Group on Lung Dynamics, 1966; Eve, 1966; Dolphin and Eve, 1966). Some summary data from these papers appears in Reference Man. It is beyond the scope of this review to discuss the respiratory tract model, but it is reviewed by Poston (1983). A new, more sophisticated respiratory tract model will be published late in

1994 or early in 1995 as ICRP Publication 66; the main elements of this model and the dosimetry for this model have been published (Bair 1991; James et al., 1991).

Chapter 1: Anatomical Values for Reference Man

Chapter 1 comprises just over half the book and contains an enormous wealth of anatomical information on the human body. Reference values have been chosen for adult males and females, listed in boldface type in the text. I have gathered most of the reference values into Table 1. ICRP Publication 23 has a similar summary table of the male data but not the female data; in addition, I have calculated certain values as % of body weight or % of lean body mass (LBM), the body weight minus body fat. The utility of normalizing by LBM is that many differences between males and females, between different population groups, and among individuals disappear or become smaller when compared on this basis. Body water on the basis of LBM, for example, is about 72-73% in animals and humans of both genders. From Table 1, first page, we see that the values for Reference Man and Reference Woman are 74.3% and 69.0%, respectively, not too far from this value, given that LBM considerations was not a criterion used by the Task Group in setting its reference values. For males and females, a variety of anatomical values for females (such as organ weights) compared with males are often between what would be predicted on the basis of body weight and what would be predicted on the basis of LBM.

As a member of the new ICRP task group that is revising Reference Man, I will point out, as I discuss ICRP Publication 23, some of the areas where we may be making changes and the philosophy behind the changes. Some changes are being made because of new data published since 1970, approximately when the cited literature ends; some changes are being made because of the inevitable errors or shortcomings in a huge task; and some changes are being made simply because points of view among the persons doing the revision are different from those on the original task group. Some opinions expressed here, however, may be my own and not necessarily express the views of the majority opinion of the new task group.

One of the most important philosophical differences is, in fact, the use of the LBM concept and the importance of body height in normalizing data being looked at and in adjusting reference values. Forbes (1987), in his book *Human Body Composition*, discusses both of these points at length. Many body anatomical and functional parameters are strongly correlated with stature. If LBM is not known, a combination of body height and body weight is often useful in setting parameters. The task group that wrote ICRP Publication 66 on the new respiratory system model used equations based on both body height and body weight in setting reference values for children and adults of each gender. Fig. 1 shows that the lean body mass differences between Caucasians and Asians is largely a matter of stature.

In the revised Reference Man, both adult males and females will probably have total body water that is consistent with 72-73% water content of the LBM. But this should be considered a minor tweaking of the numbers and not a major change, because the dosimetric consequences will be small.

Another difference in philosophy is seen in rounding. In my opinion, the rounding in ICRP Publication 23 was unnecessarily excessive — excessive because each number is rounded a great deal somewhat independently of the Reference Man model as a whole. In the human body many values are interrelated, of course, and excessive rounding makes it difficult to preserve the correct interrelationships. For example, the body height is rounded to 170 cm from 174.5 cm; I would have rounded to the nearest cm in this case, especially in light of the information that many body anatomical and functional parameters are strongly correlated with body height.

Potentially one of the most controversial changes is in the body weight of the adult male. As mentioned in the introduction, the 70-kg adult male has been a standard since at least the 1920's. Our new Reference Man will be 73 kg and 176 cm in height; our new Reference Woman will be 60 kg and 163 cm in height. The reason for the change is two-fold: (1) people are larger than they were in 1920, with 73 kg and 176 cm being closer to modern data for Europeans, our reference population; and (2) we rounded the modern data to the nearest kg rather than the nearest 5 or 10 kg. Our modern Western man is also a little fatter, and an extra 3 kg is a modest change; the American population, not used in our reference, is considerably above this 73 kg. Dosimetrically, this change will have little effect: it just makes modeling easier and more realistic.

These new adult reference sizes for height and weight have been adopted into ICRP Publication 66 on the new respiratory system model. Dose calculations currently being made for ICRP publications, such as the ongoing series ICRP Publication 56 on age-dependent dosimetry, are using the current ICRP Publication 23 body sizes. Thus, until the new Reference Man Task Group publishes its revision, there will be a slight mismatch between these calculations and the new lung model. Again, however, dosimetrically it should have rather minor consequences, and this should be viewed as a transition period.

The third page of Table 1 gives a variety of reference anatomical values from Reference Man, such as dimensions of the eye and lens, thickness of the skin and its major subdivisions, mass of contents of the GI tract, gross blood distribution in the body, and urinary capacity. Reference values for the nose and lungs are left out, because these reference values will be superseded soon by ICRP Publication 66.

Chapter 1 of Reference Man has a wealth of other anatomical information where reference values have not been chosen. Masses of organs in fetuses and children, body growth data in fetuses and children, cellular kinetics, specific gravity of organs, dimensions of organs and tissues, blood content of organs, and gross composition of organs (water, fat, protein, etc.) are among the data presented.

Chapter 2: Gross and Elemental Content of Reference Man

Chapter 2 of ICRP Publication 23 comprises primarily two large and important tables: Table 105 gives values for the physical properties (mass and specific gravity), blood content, and gross content (water, ash, fat, protein) of the various organs and tissues of Reference Man. Much of the data in this table comes from Chapter 1. Table 108 gives the elemental content of organs and tissues.

Table 2 gives excerpts from Table 105, i.e., 37 of the 114 rows of the table are shown, and all columns except that for specific gravity are shown. Table 105 summarizes data for the 70-kg adult male only. First, note that there is a lot of information in this table: 114 different categories of organs and tissues. Second, note the components (rows) that are marked with an asterisk: these quantities make up the totality of 70-kg Reference Man, i.e., the total weights add to 70,000 g, the total blood adds to 5200 ml, the total water adds to 42,000 g, etc. The other rows are usually subcategories.

Table 3 gives excerpts from Table 108, i.e., the same 37 of the same 114 organs, tissues, or compartments used in Table 105. Here, however, are data on elemental composition. Table 3 gives part of the data for four elements: nitrogen, a major element of the body; potassium, an important minor element; selenium, a trace element; and uranium, a trace element of some importance in radiation protection. Table 108 gives additional data not shown in Table 3, i.e., 80% range of the elemental composition (when available), the reference from where the value was taken, the number of subjects in the study, and the analytical method.

The elemental compositions have had two major uses in radiation protection. First, they are used in radiation transport calculations. For this purpose, however, only about 12 elements are important: the major elements N, O, H, and C; the minor elements K, Na, Cl, Ca, Mg, P, and S; and Fe, which has a high-Z number. Second, as quoted earlier from the introduction to ICRP Publication 23, they have been used in constructing retention models: "Since the uptake and retention in man of many radionuclides cannot be determined accurately, data on the corresponding stable elements are often useful for constructing a retention model and for checking the calculations" (ICRP 23, p. 1). This second use is controversial, because this approach is overly simple and can lead to substantial error in dose calculations. In fact, the current task group revising Reference Man has decided not, at this time, to revise all of Table 108. It will publish a revision only for the 12 elements important for transport calculations. Revisions for other elements may or may not be done later, depending on the perceived need.

Users need to be cautious when using Table 108 on elemental composition. Research subsequent to publication of Reference Man has shown that for a number of trace elements the older analytical techniques were not adequate to give meaningful results or contamination of samples was a problem (Iyengar, 1985, and personal communication). For selenium there is apparently a serious error in the blood concentration given, and a researcher has published a warning against using the selenium data in Reference Man. There are errors in the data for sodium, and Mole (1984) has published a paper giving his model for sodium in the body, which is important in neutron dosimetry for persons accidentally exposed to large neutron fields. And for environmental contaminants such as lead or mercury, there is always the problem of getting meaningful reference values (I have no reason to question the values in Reference Man; this is a general consideration or problem). A correspondent to the new task group pointed out an interesting anomaly: Table 110 of Reference Man gives silicon as the 12th most abundant element in the body, at 18 g, but Table 108 gives no information on where the silicon resides.

Chapter 3: Physiological Data for Reference Man

Chapter 3, labeled physiological data, is a grab-bag of miscellaneous information thought to be useful for radiation protection. It includes respiratory standards (soon to be superseded by ICRP Publication 66), energy expenditure, various data on dietary intake, urinary and fecal losses, milk and fluid consumption, a model for water balance, composition of sweat, saliva, and nasal secretion, flow of nasal secretion, and a large section with model values for daily balance of 51 elements in Reference Man.

Much of these data are useful, especially those for water balance and urinary and fecal losses. Table 4 gives the model values for water balance for an adult man, an adult woman, and a 10-year-old child. In non-temperate climates, these values would need to be modified considerably.

published (Bair 1991; James et al. 1991). It supersedes, of course, all respiratory reference values given in ICRP Publication 23.

New Task Group to Revise Reference Man

A task group to revise Reference Man was set up in the mid-1980s, first under the chairmanship of Chester R. Richmond and now under the chairmanship of Keith F. Eckerman. Initially, the task group set out to revise the entire document, plus adding some sections and including data that might be of use outside radiation protection because of the widespread use of the document. We were somewhat slow in getting a proper appreciation of just how enormous the task of the original task group on Reference Man was, but it soon became evident that we had neither the resources in manpower or funding to do what we had at first proposed (part of the problem is related to the trend away from core funding by national agencies that in the past has supported much of the work for the ICRP). The task group has completed or nearly completed a lot of good-quality data on Reference Man, albeit much more limited than that in ICRP Publication 23. Consequently, the task group has decided to revise only certain parts of ICRP Publication 23 and in piecemeal fashion, hoping to beat the Dead Sea Scrolls to full publication. The first one or two publications will include the following sections:

I. Anatomical Values for Reference Man. Data for children and adults on total body height and weight, surface area, total body water, intracellular and extracellular water, blood volume in total body and a new model for blood volume in individual organs, body fat content, adipose tissue, and organ masses.

II. Gross Content of the Body and Organs and Tissues of the Body. Elemental content for 12 elements only (those important in radiation transport).

III. Physiological Data for Reference Man. Respiratory parameters (summarized from ICRP Publication 66). Water balance. Urinary and fecal excretion. A new blood flow model. Cardiac output. Gastrointestinal tract residence times.

IV. Skeleton. A major modification of the section on the skeleton.

V. Data for Asian Populations.

A later publication is planned for the GI tract, probably including a new GI tract model for dosimetry. Other sections may be planned and executed later, as it seems vital for radiation protection and as resources are available.

Important Changes/New Information in Revised Reference Man

The revised Reference Man will continue to be a Westerner. Although the publications will include data compiled by G-I. Tanaka primarily on the Japanese population, which he believes appropriate for most Asian populations, the task group decided not to attempt a World Reference Man at this time. This is difficult, controversial, and politically sensitive issue. I will give my own opinion here. First, it is tempting to devise a world anatomical model, because, frankly, radiation doses are not very sensitive to small differences in adult body size and probably even less to the often smaller differences in sizes of children of a given age among populations. A lot of effort has been given by various national radiation protection bodies in developing organ mass data, body size data, and phantoms appropriate for their countries. (The work of Yamaguchi (e.g., 1984) in Japan on adapting Western dosimetric data to other populations has been underappreciated, in my opinion.) However, dosimetrically these considerations are dwarfed by considerations of biokinetics, physiology, and diet. However, at this time I favor staying with the Western model for the following reason: with some exceptions, the large body of quality data upon which one bases anatomical, physiological, and biokinetics models are Western data on Western subjects. It is scientifically easier to have all of these models based on similar and consistent data than to mix and match and thus scale some of the data. But it's a close call, and the notion of a World Reference Man for Purposes of Radiation Protection should be discussed further.

We are also changing the adult age from a young adult, range 20-30 years, to a young-to-middle-aged adult with a larger age range, 20-50 years, for several reasons: (1) the body is still maturing in many ways during the 20's, and many anatomical and physiological parameters reach a plateau in the 30's before declining after age 45 or so; or if there is a steady decline from young adults to old, a middle value is more representative as a reference value for adulthood than is a value for young adults. (2) Much of the data we are using comes from combining data from young and middle-aged adults, roughly from ages 18 or 20 to 50, for practical reasons of availability of data. We usually exclude older adults because of changes in the body that can be substantial, especially after age 70. A reference that is an average over this larger range would better approximate an adult over most of the period used in dose calculations; and if it became necessary to account for aging processes, a second model to cover ages 50-70 would probably suffice. (4) The data used to define the current ICRP Reference Man often include data on middle-aged adults, especially when data on the 20-30-year age group were sparse, without adjustment for probable age effects. Thus the current ICRP Reference Man is a little older than advertised.

The new section on the skeleton, written by R.W. Leggett, is especially noteworthy. In the course of his biokinetics modeling on radionuclides going to the skeleton, he has improved the Reference Man data substantially. His skeletal data are used in the models and dosimetry for the ongoing series ICRP Publication 56 on age-dependent dosimetry, so that, in a way, they are already the *de facto* Reference Man skeleton now, although not formally published as such. This section presents much new data as well as reorganizing the old.

White and Woodard, in several recent papers, have thoroughly reworked and modeled data on elemental compositions of organs and tissues, including children. Their papers will be used extensively.

Fomon (1982) has developed models for gross and some elemental composition of the total body in children. For adults Ellis (1990) has published useful information on gross and some elemental composition from a large collection of neutron activation studies.

Tanaka has published original autopsy data on organ masses in modern Japanese children and adults. Most of the Western autopsy data is old (1930s or earlier) and with smaller sample sizes. We are investigating using a combination of appropriately scaled Japanese data, for some organs, and the older Western data to get better estimates for the reference Westerner. The potential for *in vivo* measurements with modern imaging techniques has been available for some time, but few studies have been published; and even among those published, the results are sometimes not believable. One recent fascinating study showed a large diurnal variation in volume of the liver, a result that needs to be confirmed and checked on other organs.

The data on dietary intake are less useful. The ICRP's current approach on dose calculations is to publish dose-per-unit intake and leave the users to use whatever intake data is appropriate for the purpose. Groups like the World Health Organization are currently compiling world-wide data on gross and elemental composition of representative diets, and many national radiation protection bodies have compiled or are compiling dietary information for their countries. The International Atomic Energy Agency is also involved with this work. Wide variations world-wide in iodine content of the diet are well-known and have important consequences in iodine dosimetry, for example, with Japanese having very high intakes.

In my opinion, the weakest part of Reference Man is the large section on model balances for the 51 elements. It seems to me that, given both the manpower available to the task group and the quantity and quality of data available, the task was much too ambitious. For many elements the data are just not of sufficient quality to make a reasonable model, and presenting a model in such situations can be misleading. Dosimetrists needing such information should be cautious when using these data, and for some elements new models may need to be constructed.

ICRP REFERENCE MAN, WORK IN PROGRESS

New Respiratory Tract Model, ICRP Publication 66

As mentioned previously, a new respiratory tract model developed by a task group of Committee II of the ICRP will be published, probably in late 1994, as ICRP Publication 66. Overviews of the model and dosimetry developed for the model have already been

Two Controversies Renewed

I want to end by renewing two controversies, one on nitrogen content of muscle and the other on sodium content of the body. Woodard and White (1986) have criticized the nitrogen content of muscle in Reference Man. And, as mentioned earlier, Mole (1984) criticized the sodium composition in ICRP Publication 23 and gave his own model.

Since 1964 the ICRU has used 3.5% as their reference value for human skeletal muscle. It is based on an obscure Swiss business publication, one that I have never been able to acquire. In ICRP Publication 23, the reference value was given as 2.8%. Woodard and White have criticized this value as too low, believing that it was based partly on pediatric data. They came up with a value of 3.4%, close to the ICRU value of 3.5%, based on their evaluation of literature data. My own analysis, using mostly the same data used by them, resulted in a value of 3.1%. (I agree with them that the Reference Man value is too low, although the error seems to be for another reason. Reference Man nitrogen content appears to be based largely on data from Widdowson, who gave N content of muscle as 2.8% protein N and 0.3% non-protein N. The error appears to be in forgetting the latter component.) It appears to me that Woodard and White used values given in the literature for protein content, which were changed to nitrogen values by assuming that protein is 17% nitrogen. However, these protein values were apparently derived from measurements of the nitrogen, and the protein values were secondary values, with the assumption that protein is 16% nitrogen. Thus, Woodard and White's value of 3.4 should really be 3.4 x 16/17, or 3.2, very close to my value of 3.1. In fact, they are even closer than this: a detailed analysis using their data gave 3.16, rounded to 3.2, and my value of 3.1 was rounded from 3.14. The slight difference is due to slight differences in the literature data selected. Kim (1974) gives a reference value of 3.2%.

The sodium question is more complex, and I am less sure of the point of contention I am about to raise. But it is potentially important, and if my reasoning turns out to be incorrect, so be it, someone will correct me. Let me first review briefly the problem Mole had with ICRP Publication 23, in order to set up the problem I may have with Mole's model. Table 4 is an expansion of Mole's Table 3, which gives the ICRP values for sodium in various compartments as given by Mole, the same data as corrected in the 1981 printing of ICRP Publication 23, and Mole's model. The "total" values are given in ICRP, and the concentration values are derived by Mole. Unfortunately, the 1975 original printing had columns in the sodium table misaligned, so that Mole misread the sodium data for red marrow, yellow marrow, cartilage, and periarticular tissue, and further led to an error in his calculation in deriving an ICRP value for bone by difference. Even with this correction, however, there are major differences between Mole's model and the ICRP values, and Mole's objections are still valid. But I will be comparing the corrected ICRP values with Mole's model and with some of my own preliminary calculations from here on.

ICRP has 100 g Na in total body; Mole has 75. ICRP has 68 g in total soft tissue; Mole has 40. ICRP has 32 g Na in skeleton, similar to Mole's 35 g, but it is distributed differently within the skeleton. There are similar estimates for yellow marrow (0.66 vs. 0.6 g), but ICRP has much more Na in the cartilage and periarticular tissue (6.0 vs. ~1 and 4.9 vs. ~2). Mole has 1.5 g Na in the red marrow; ICRP does not give a value. Mole has most of the skeletal sodium in bone (calcified tissue), 30 g. ICRP does not give a value, but by difference its maximum value would be 20.4 g, depending on how much is assigned to red marrow. If we assign Mole's 1.5 g to red marrow, ICRP's bone value would then be about 19 g, substantially less than Mole's value. An interesting note in passing is that Woodard and White's elemental tissue compositions for cartilage and periarticular tissue are 5 and 2 g/kg, respectively. That is, their cartilage composition with agrees with ICRP but their periarticular composition agrees with Mole. I have not investigated this disagreement.

I am going to argue, by two different routes, that total body sodium may be in the range 85-95 g for the new Reference Man of 73-kg weight, 176 cm height, and age 20-50 years. ICRP's and Mole's value for this 73-kg man would be about 104 g and about 78 g from the body weight difference. That is, I will be giving evidence for a total body sodium value about half-way between these two values.

Argument 1. Assume Mole's value of 6.0 g/kg Na in bone, but use new Reference Man value of 5.5 kg bone, giving 33.0 g Na in bone. Assume that the rest of sodium is in the intracellular water (ICW) plus extracellular water (ECF), and that the total body water (TBW) can be split completely between these two compartments. Assume that Reference Man has 20% fat and that the lean body mass, LBM (or fat free mass, FFM) is 73% water. Thus TBW = 42.6 liter. Use three different regression equations from the literature for the relationship between ECF and TBW, as given in Forbes (1987), which yield estimates of ECF as 16.6, 18.0, and 18.0 liters. Assume 3.30 g/l Na in ECF and 10 mmol/l, or 0.230 g/l Na in ICF. Subtract out 2.1 g Na in bone water, as 0.122 g/g bone water * 5500 g bone = 671 g water -> 2.1 g Na if all water is ECF. This yields 58.6 - 62.9 g Na in the combined ECF + ICF, and adding the 33.0 g Na in bone gives a total of 91.6 - 95.9 g Na in the body.

Argument 2. Adding up the body as the sum of all its organs and tissues, putting the new Reference Man with its 5.5 kg bone and 30 kg muscle and other organs as in ICRP

Publication 23, and using mostly sodium compositions from Woodard and White (1986) except for Mole's bone value and an independent assessment of muscle sodium, and taking into account some ranges of possible compositions, especially in the huge muscle compartment, total body sodium ranged from 85.5 to 97.1 g.

Other Evidence. Using data from neutron activation studies of Ellis (1990) that the FFM contains 0.141 g/kg Na and assuming that all sodium is in the FFM, then total body Na = 73 kg * 0.80 FFM/TBM * 0.141 g/kg Na = 82.3 g. Mole gives 3 prediction equations for total body sodium, also based on neutron activation studies. These prediction equations give estimates of 81.3, 85.7, and 76.2 g for the new Reference Man. The grand mean of these 4 predictors, all based on neutron activation studies, is 81.4 g, smaller than the ranges of estimates given by the two arguments above and only marginally higher than our "Mole's adjusted estimate" of 78 g sodium for 73-kg Reference Man.

The Crux of the Possible Disagreement. Mole's evaluation is based on three major arguments/assumptions: (1) Neutron activation studies give an accurate assessment of total body sodium; (2) there is a lot of sodium in calcified bone tissue (30-33 g, depending upon whether we use the old or the new Reference Man skeleton); and (3) the overwhelming majority of sodium is bone is exchangeable, since measured values of exchangeable sodium are about 68-69 g in a 73-kg man (from 2 prediction equations given by Mole). Assumption # 2 is solid, I believe. I don't know about assumption # 1. Assumption # 3 is controversial and may be the answer to which evaluation, mine vs. Mole's, gives the better estimate. Forbes (1987, pp. 22-23) says that only about 15% of bone cortex Na undergoes exchange with serum Na, which would be consistent with a total body Na of about 96-97 g. Mole says that 25-50% exchangeability is commonly quoted, but believes from his Na analysis that about 75% must be exchangeable. I would suggest that a definitive answer on the bone-sodium exchangeability problem is necessary to settle the issue.

REFERENCES

Bair, W.J. Overview of ICRP Respiratory tract model. Radiat. Prot. Dosim. 38: 147-152; 1991.

Chalk River Conference. Minutes of the Permissible Doses Conference held at Chalk River, Canada, September 29th-30th, 1949. RM-10, 1950. [The copy I have is labelled "R.M.-10", is 19 pages, is undated, and is originally from the files of Mary Rose Ford. See comments of Taylor (1979), p. 7-082, about various minutes from this meeting. ICRP Publication 23 gives publication information as "RM-10, 1950." Poston (1983) attributes the publication to the NCRP.]

Dolphin, G.W.; Eve, I.S. Dosimetry of the gastrointestinal tract. Health Phys. 12: 163-172; 1966.

Ellis, K.J. Reference Man and Woman more fully characterized: Variations on the basis of body size, age, sex, and race. In: Schrauzer, G.N., ed. Biological trace element research. The Humana Press; 1990.

Eve, I.S. A review of the physiology of the gastrointestinal tract in relation to radiation doses from radioactive materials. Health Phys. 12: 131-161; 1966.

Fomon, S.J. Body composition of reference children from birth to age 10 years. Am. J. Clin. Nutr. 35: 1169-1175; 1982.

Forbes, G.B. Human body composition. Growth, Aging, Nutrition, and Activity. New York: Springer-Verlag; 1987.

International Commission on Radiological Protection. Report of Committee II on permissible dose for internal radiation. New York: Pergamon Press; ICRP Publication 2; 1959.

International Commission on Radiological Protection. Report of the Task Group on Reference Man. Oxford: Pergamon Press; ICRP Publication 23; 1975.

International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides: Part 1. Oxford: Pergamon Press; ICRP Publication 56, Part 1; Annals of the ICRP 20 (2); 1989.

International Commission on Radiological Protection. Human respiratory tract model for radiological protection. Oxford: Pergamon Press; ICRP Publication 66; Annals of the ICRP 24 (1-4); in press.

Iyengar, G.V. Sample collection, treatment, preservation and storage of biomedical specimens for trace element analysis. Quality assurance considerations. In: Trace elements in health and disease; Skandia International Symposia. Stockholm: Almqvist & Wiksell International; 1985; 64-79.

James, A.C.; Gehr P.; Masse, R.; Cuddihy, R.G.; Cross, F.T.; Birchall, A.; Durham, J.S.; Briant, J.K. Dosimetry model for bronchial and extrathoracic tissues of the respiratory tract. Radiat. Prot. Dosim. 37: 221-230; 1991.

Kim, Y.S. Human tissues: chemical composition and photon dosimetry data. Radiat. Res. 57: 38-45; 1974.

Mole, R.H. Sodium in man and the assessment of radiation dose after criticality accidents. Phys. Med. Biol. 29: 1307-1327; 1984.

Task Group on Lung Dynamics (Morrow, P.E.; Bates, D.V.; Fish, B.R.; Hatch, T.F.; Mercer, T.T.). Deposition and retention models for internal dosimetry of the human respiratory tract. Health Phys. 12: 173-207; 1966.

Poston, J.W. Reference Man: A system for internal dose calculations. In: Till, J.E.; Meyer, H.R., eds. Radiological assessment: A textbook on environmental dose analysis. Washington, D.C.: U.S. Nuclear Regulatory Commission; NUREG/CR-3332, ORNL-5968; 1983: ch. 6, 1-31.

Taylor, L.S. Organization for radiation protection. The operations of the ICRP and NCRP, 1928-1974. U.S. Department of Energy: DOE/TIC-10124; 1979.

Woodard, H.Q., and White, D.R. The composition of body tissues. Br. J. Radiology 59: 1209-12-18; 1986.

Yamaguchi, H. Estimation of internal radiation dose for various physiques using MIRD adult absorbed fractions. Chiba, Japan: National Institute of Radiological Sciences, NIRS-M-51; 1984.

Table 1. Anatomical Characteristics of Reference Man and Woman.

The % body and % LBM (Lean Body Mass) value are in per cent or in liters/kg x 100. Reference Woman values tagged with a † were chosen to be 58/70 of the male value, i.e., scaled on body weight.

	REFERENCE MAN			REFERENCE WOMAN		
Characteristic	Value	% body	% LBM	Value	% body	% LBM
Weight	70 kg			58 kg		
Height	170 cm			160 cm		
Surface Area	0.018 m^2			0.016 m^2		
Sp. Gravity	1.07			1.04		
Fat:						
Nonessential	12 kg			15 kg		
Essential	1.5			1		
Total	13.5	19.3		16	27.6	
Lean Body Mass (LBM is weight - fat)	56.5 kg			42 kg		
Body Water:						
Intracellular	23.8 ℓ	34.0	42.1	17.4 ℓ	30.0	41.4
Extracellular	18.2	26.0	32.2	11.6	20.0	27.6
Total	42.0	60.0	74.3	29.0	50.0	69.0
Blood:						
Red Blood Cells	2200 mℓ			1350 mℓ		
	2400 g	3.4	4.2	1500 g	2.6	3.6
Plasma	3000 mℓ			2500 mℓ		
	3100 g	4.4	5.5	2600 g	4.5	6.2
Total	5200 mℓ			3900 mℓ		
	5500 g	7.9	9.7	4100 g	7.1	9.8
Lymphatic System:						
Lymphocyes	1500 g	2.1	2.7	1200 g†	2.1	2.9
Fixed Lymph. Tiss	700	1.0	1.2	580†	1.0	1.4
Adipose Tissue:						
Subcutaneous	7.5 kg	10.7		13.0 kg	22.4	
Separable	5.0	7.1		4.0	6.9	
Yellow Marrow	1.5	2.1		1.3	2.2	
Interstitial	1.0	1.4		0.7	1.2	
Total	15.0	21.4		19.0	32.8	
Connective Tissue:						
Cartilage	2500 g	3.6	4.4	2000 g	3.4	4.8
Tendons & Fascia	850	1.2	1.5	700	1.2	1.7
Other Conn. Tiss.	1700	2.4	3.0	1400	2.4	3.3
Total	5050	7.2	8.9	4100	7.1	9.8

Table 1 (cont'd). Anatomical Characteristics of Reference Man and Woman.

Values are in grams unless noted otherwise.

	REFERENCE MAN			REFERENCE WOMAN		
Characteristic	Value	% body	% LBM	Value	% body	% LBM
Skeleton	10000	14.3	17.7	6800	11.7	16.2
Bone	5000	7.1	8.8	2600	4.5	6.2
Cortical	4000	5.7	7.1	2080	3.6	5.0
Trabecular	1000	1.4	1.8	520	0.9	1.2
Red Marrow	1500	2.1	2.7	1300	2.2	3.1
Yellow Marrow	1500	2.1	2.7	1300	2.2	3.1
Skel. Cartilage	1100	1.6	1.9	900	1.6	2.1
Periartic. Tissue	900	1.3	1.6	700	1.2	1.7
Skeletal Muscle	28,000	40.0	49.6	17,000	29.3	40.5
Skin	2600	3.7	4.6	1790	3.1	4.3
Brain	1400	2.0	2.5	1200	2.1	2.9
Spinal Cord	30			28		
Cerebrospinal Fluid	120 mℓ			100 mℓ		
Eyes	15			15		
Lenses	0.4			0.4		
Lungs	1000	1.4	1.8	800	1.4	1.9
Pulmonary Blood	530			430		
Lung Tissue	440			360		
Bronchial Tree	30			25†		
Major Organs, Trunk						
Liver	1800	2.57	3.19	1400	2.41	3.33
Kidneys	310	0.44	0.55	275	0.47	0.65
Spleen	180	0.26	0.32	150	0.26	0.36
Pancreas	100	0.14	0.18	85	0.15	0.20
Heart	330	0.47	0.58	240	0.41	0.57
GI tract, w/o cont	1200	1.71	2.12	1100	1.90	2.62
Esophagus	40	0.06	0.07	34	0.06	0.08
Stomach	150	0.21	0.27	140	0.24	0.33
Intestine	1000	1.43	1.77	950	1.64	2.26
SI	640	0.91	1.13	600	1.03	1.43
LI	370	0.53	0.65	360	0.62	0.86
Adrenals	14			14		
Thyroid	20			17†		
Thymus	20			20		
Sex-related Organs:						
Breasts	26			360		
Uterus				80		
Ovaries				11		
Fallopian Tubes				2		
Testes	35					
Prostate	16					

Table 1 (cont'd). Anatomical Characteristics of Reference Man and Woman.

	REF. MAN	REF. WOMAN
Characteristic	Value	Value
Other Organs:		
Gall Bl. Wall	10 g	8† g
Parathyroids	0.12	0.14
Pineal Gland	0.18	0.15
Pituitary	0.6	0.7
Urinary Bl. Wall	45	45
Tongue	70	60
Salivary Glands	85	70†
Tonsils	4	4
Larynx	28	19
Trachea	10	8†
Ureters	15	15
Urethra	10	3
Other Anatomical Values:		
Blood (distribution in total body)		
Arterial system	1000 mℓ	750 mℓ
Venous system	3200 mℓ	2400 mℓ
Pulmonary system	500 mℓ	400 mℓ
Heart cavity (av. value)	500 mℓ	350 mℓ
Skin thickness	1300 μm	1300 μm
Epidermis	50 μm	50 μm
Dermis	1250 μm	1250 μm
Hypodermis thickness	3750 μm	6600 μm
GI tract (contents)	1005 g	not given
Stomach	250 g	not given
Small intestine	400 g	not given
Upper large intestine	220 g	not given
Lower large intestine	135 g	not given
Intestinal tract (length)	660 cm	not given
Small intestine	500 cm	not given
Large intestine	160 cm	not given
Lens (depth and size)		
Anterior aspect of lens to anterior pole of cornea	0.3-0.4 cm	0.3-0.4 cm
Anterior aspect of lens to anterior aspect of closed lens	0.8 cm	0.8 cm
Equator of lens to anterior of corneal border	0.3 cm	0.3 cm
Equatorial diameter of lens	0.9 cm	0.9 cm
Axial thickness of lens	0.4 cm	0.4 cm
Respiratory system (superceded by ICRP 66)		
Urinary bladder capacity		
Capacity (distress)	500 mℓ	500 mℓ
Physiological capacity	200 mℓ	200 mℓ

Table 2. Excerpts from the Famous Table 105 of ICRP Publication 23: Physical Properties, Blood Content, and Gross Content of Reference Man. Asterixed quantities make up the totality of Reference Man.

Organ, tissue, or component	Weight (g)	Total blood (ml)	Resid. Blood (ml)	Water (g)	Ash (g)	Fat (g)	Protein (g)
1 Total body	70000	5200	..	42000	3700	13500	10600
2 Adipose tissue	15000	270	270	2300	30	12000	750
3 Subcutaneous*	7500*	140*	140	1100*	15*	6000*	380*
4 Other separable*	5000*	90*	90	750*	10*	4000*	250*
5 Interstitial	1000	..	..	150	2	800	50
6 Yellow marrow	1500	20	..	230	3	1200	60
7 Adrenals (2)*	14*	3.3*	0.6	8*	0.06*	3.6*	2.2*
8 Aorta*	100*	..	..	70*	1.4*	1.5*	27*
9 Contents*	190*	180*	..	150*	1.9*	1.2*	34*
10 Blood	5500	5200	..	4400	55	36	990
11 Plasma	3100	..	..	2900	29	23	210
12 Erythrocytes	2400	..	..	1500	26	13	780
13 Blood vessels*	200*	..	..	150*	1.2*	..	48*
14 Contents* (except aorta and pulmonary)	3000*	2900*	..	2400*	30*	20*	540*
26 Separ. conn. tiss.*	1600*	..	..	1000*	66*	21*	580*
27 Central nervous sys.*	1430*	32*	..	1100*	21*	160*	110*
28 Brain	1400	31	..	1100	21	150	110
29 Cerebrum	1200	..	..	930	18	130	96
30 Cerebellum	150	..	..	120	2.3	13	12
31 Brain stem	30	..	..	23	0.45	3.3	2.4
32 Spinal cord	30	..	..	..	..	..	..
33 Cerebrospinal fluid*	120*	..	..	120*	0.8*	..	0.03*
34 Eyes (2)*	15*	..	..	..	..	..	..
38 GI tract*	1200*	..	..	950*	10*	74*	160*
39 Contents*	1005*	..	..	900*	..	..	..
61 Hair*	20*	..	..	1.7*	0.10*	0.5*	18*
62 Heart*	330*	53*	13	240*	3.6*	33*	55*
63 Contents (av.)*	500*	500*	..	400*	5*	3.3*	90*
64 Kidneys (2)*	310*	70*	25	240*	3.4*	16*	53*
65 Larynx*	28*	..	..	19*	0.84*	..	..
66 Liver	1800*	250*	..	1300*	23*	120*	320*
67 Lung*	1000*	530*	100	780*	11*	9.9*	177*
77 Muscle (skeletal)*	28000*	700*	250	22000*	340*	620*	4800*
88 Skeleton*	10000*	350*	..	3300*	2800*	1900*	1900*
96 Skin*	2600*	65*	..	1600*	18*	260*	750*
113 Urinary bladder*	45*	..	..	29*	0.36*	..	..
114 Contents (urine)*	102*	..	..	95*	1.1*	..	6.2*

Table 3. Excerpts from the Famous Table 108 of ICRP Publication 23: Elemental Content of Organs and Tissues of Reference Man. Asterixed quantities make up the totality of Reference Man.

Organ, tissue, or component	Weight (g)	Nitrogen (g)	Potassium (g)	Selenium (g)	Uranium (g)
1 Total body	70000	1.8E+3	1.4E+2	(see text for blood Se disc.)	9.0E-5
2 Adipose tissue	15000	1.2E+2	4.8		9.0E-6
3 Subcutaneous*	7500*	6.1E+1*	2.4*		4.5E-6*
4 Other separable*	5000*	4.0E+1*	1.6*		3.0E-6*
5 Interstitial	1000	8.0	2.6E-1		6.0E-7
6 Yellow marrow	1500				
7 Adrenals (2)*	14*	0.4*	1.4E-2*		
8 Aorta*	100*	4.3*	1.2E-1*		
9 Contents*	190*	5.4*	3.1E-1*	3.8E-5*	1.6E-7*
10 Blood	5500	1.6E+2	8.8	1.1E-3	4.6E-6
11 Plasma	3100	3.4E+1	5.0E-1		
12 Erythrocytes	2400	1.3E+1	8.3		
13 Blood vessels*	200*				
14 Contents* (except aorta and pulmonary)	3000*	8.6E+1*	4.8*	6.0E-4*	2.1E-6*
26 Separ. conn. tiss.*	1600*	9.3E+1*			
27 Central nervous sys.*	1430*	1.8E+1*	4.2*	2.9E-4*	
28 Brain	1400	1.8E+1	4.2	2.9E-4	
29 Cerebrum	1200	1.5E+1	3.7		
30 Cerebellum	150	1.9	4.5E-5		
31 Brain stem	30	3.8E-1	9.0E-2		
32 Spinal cord	30				
33 Cerebrospinal fluid*	120*	5.4E-3*	1.2E-2*		
34 Eyes (2)*	15*				
38 GI tract*	1200*	2.6E+1*	1.5*	2.2E-4*	
39 Contents*	1005*				
61 Hair*	20*	2.9*			
62 Heart*	330*	8.8*	7.2E-1*	7.5E-5*	5.3E-8*
63 Contents (av.)*	500*	1.4E+1*	6.3E-1*	1.0E-4*	4.2E-7*
64 Kidneys (2)*	310*	8.5*	5.9E-1*	2.9E-5*	7.0E-6*
65 Larynx*	28*		3.9E-2*		
66 Liver	1800*	5.1E+1*	4.5*	1.2E-3*	4.5E-7*
67 Lung*	1000*	2.8E+1*	1.9*	1.8E-4*	1.0E-6*
77 Muscle (skeletal)*	28000*	7.7E+2*	8.4E+1*	5.0E-3*	5.3E-6*
88 Skeleton*	10000*	3.0E+2*	1.5E+1*		5.9E-5*
96 Skin*	2600*	1.2E+2*	2.2*		
113 Urinary bladder*	45*		6.3E-2*		
114 Contents (urine)*	102*	1.0*	2.0E-1*		

Table 4. Sodium in Reference Man (1975), Reference Man (as corrected in 1981 printing), and Mole (1984). The superscripts 1, 2, and 3 identify the same data in the two columns for ICRP (1975) and ICRP (1981 printing). The 1975 edition had columns in the sodium table partially mismatched, causing Mole to misread the data on red marrow, yellow marrow, cartilage, and periarticular tissue, and further led to an error of his calculation of sodium in bone by difference.

Compartment or Organ	Fresh tissue mass (kg)	ICRP 1975, as given by Mole		ICRP, 1981 printing		Mole's model, 1984	
		Total (g)	Conc. g/kg	Total (g)	Conc. g/kg	Total (g)	Conc. g/kg
Total body	70	100	1.4	100	1.4	75	1.07
Total soft tissue	60	68	1.1	68	1.1	40	0.67
Skeleton	10	32	3.2	32	3.2	35	3.5
Bone (calcified tissue)	5	Not given. By difference, 16	3.2	Not given. By difference, up to 20.4	Up to 4.1	30	6.0
Red Marrow	1.5	0.66[1]	0.44	Not given		1.5	1.0
Yellow Marrow	1.5	6.0[2](sic)	4.0?	0.66[1]	0.44	0.6	0.4
Cartilage	1.1	4.9[3]	4.5	6.0[2]	5.5	~1	~1
Periarticular tissue	0.9	4.7	5.2	4.9[3]	5.4	~2	~2

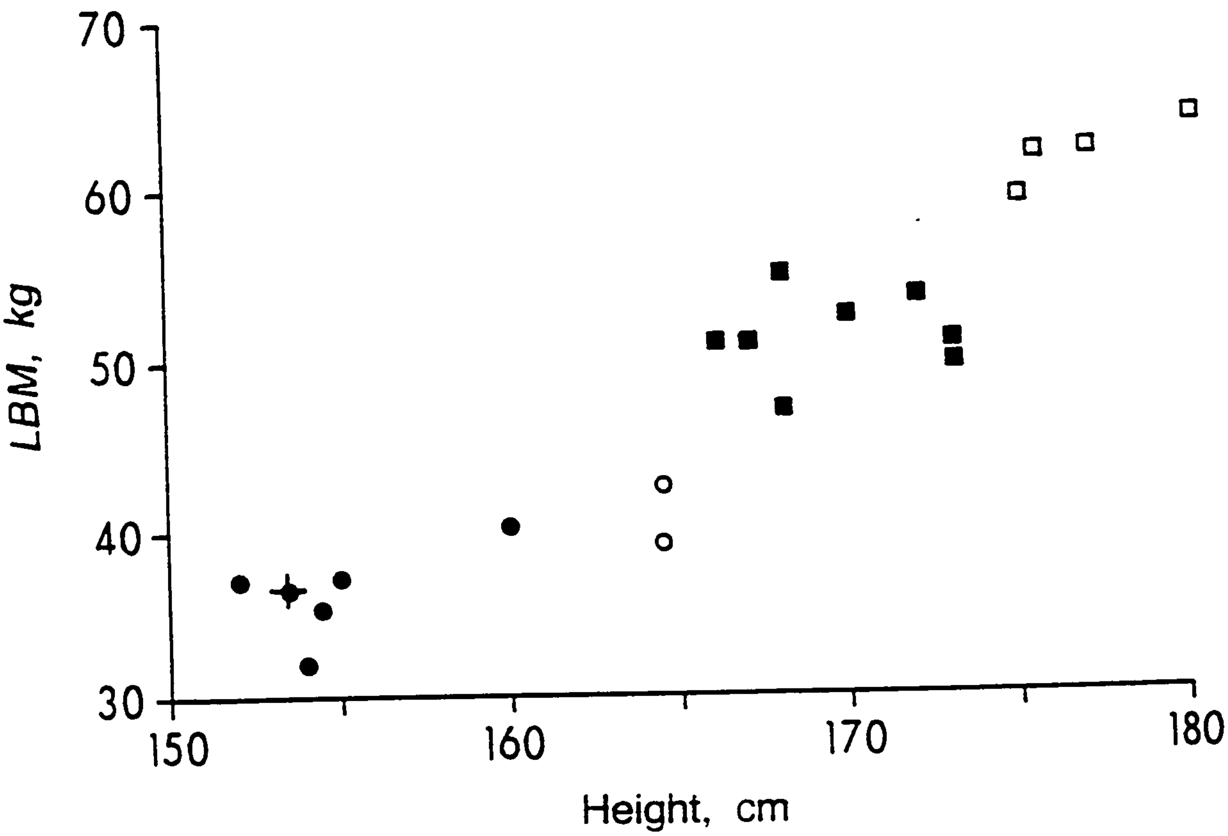

Fig. 1. Plot of lean body mass, LBM, against stature. Circles are women; squares are men; filled symbols are Asians; open symbols are Caucasians. Data collected from a variety of studies and plotted by Forbes (1987).