Total body potassium and body fat: relevance to aging\textsuperscript{1-4}

Joseph J Kehayias, Maria A Fiarorone, Hong Zhuang, and Ronenn Roubenoff

ABSTRACT

Understanding the mechanisms that govern sarcopenia (depletion of muscle mass with age) may suggest ways to preserve lean tissue and functional capacity, and to maintain quality of life in the elderly. We investigated the body-composition changes in normal aging in a cross-sectional study of 188 healthy volunteers aged 20–89 y, which examines the differences in body cell mass and fat as a function of age. In aging, the assumptions of indirect body-composition-measurement techniques, such as the “constant” hydration coefficient of lean body mass or the “constant” density of fat-free mass, may not hold. Therefore, we selected body-composition-measurement techniques that are not sensitive to assumptions about the composition of lean tissue. Cellular mass, lean body mass, and fat were assessed “directly” by total body potassium (TBK) measurements and neutron inelastic scattering. Our results show that TBK content declines at a rate of 7.20 ± 1.00 mg K· kg body wt\textsuperscript{-1}·y\textsuperscript{-1} for females (r = 0.601, P ≤ 0.001) and 9.16 ± 0.96 mg K· kg body wt\textsuperscript{-1}·y\textsuperscript{-1} for males (r = 0.710, P ≤ 0.001). Body fat measurements by neutron inelastic scattering have shown a significant increase of percentage body fat with age for female volunteers between the ages of 20 and 50 y and a continuous increase for male volunteers throughout adult life. Am J Clin Nutr 1997;66:904–10.

KEY WORDS

Body composition, potassium, fat, neutron inelastic scattering, aging, sarcopenia, humans

INTRODUCTION

Adult body composition changes during normal aging, starvation, malnutrition, disease, and medical interventions such as major surgery, radiation treatment, or chemotherapy. There is an additional discrete category of conditions promoting body-composition changes, which are not necessarily involuntary, such as the use of anabolic steroids, systemic intense exercise, anorexia nervosa, treatment with growth hormone, or use of antistress pharmaceuticals. An important question accompanies the conditions described above: what is the most appropriate measurement method for monitoring changes in lean body mass and adipose tissue? Several investigators have addressed this question for specific populations such as the elderly, athletes, and critically ill patients (1–5). The traditional approach, which is still used, is based on anthropometry. Body weight by itself or body weight compared with height, such as body mass index, has been used to classify individuals as lean, average, or obese. Similarly, change in body weight has been the chief clinical criterion for changes in nutritional status of patients. This approach, although crude and of limited value in providing correct information on the changes of lean body mass, is often used successfully by clinicians. This is because it is not used alone but combined with other indexes characterizing the progress of the condition and the overall experience of the physician.

Other investigators have taken a more analytic approach to assessing body composition by measuring a physical property of the body and deriving from that the lean body mass. Examples of this approach are measurements of body density by hydrodensitometry (6) and electrical resistance and reactance by bioelectrical impedance analysis (7). This approach has been extended to include imaging techniques that rely on the difference of the physical properties of different tissues. Computerized tomography has been used for the assessment of fat and lean tissue (8), and more recently, magnetic resonance imaging and dual-photon X-ray absorptiometry (9, 10).

The most analytic approach to monitoring lean body mass is the measurement of all its components. Cohn et al (11) derived a model according to which water, bone ash, and protein are measured individually by tritiated water dilution, delayed neutron-activation analysis, and prompt-gamma neutron activation, respectively. Their sum represents the majority (> 98%) of total body lean mass. (Body glycogen, a small, variable, nonmeasurable compartment, is calculated as a function of the body’s protein.) This technique is often referred to as the “four-compartment model” and is ideal for the investigation of the details, for example, of catabolic conditions, obesity, and osteoporosis because it monitors each compartment independently. Unfortunately, its use is limited by the availability and cost of the required neutron-activation facilities.

A simpler approach to assessing lean body mass is to measure a single component of lean tissue. Total body water (TBW) and total body potassium (TBK) are the most successful examples of this approach. The TBW method relies on the assumption that water is a constant fraction of lean tissue. The constant hydration hypothesis seems to hold, on average, in all

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but the most extreme cases of obesity, edema, and dehydration. TBK was used originally under the assumption of constant potassium content of lean body mass. The development of techniques such as the neutron-activation approach described above have shown this assumption to be incorrect (5,11). TBK measures something different, the intracellular mass or body cell mass (BCM) as suggested by Moore et al in 1963 (12). BCM is the metabolizing, oxygen-consuming portion of lean body mass. It does not always serve successfully as the lean mass predictor because the content of cell mass within the lean tissue is variable and condition dependent. We suggest that TBK, despite its limitations in assessing lean body mass, is the best single predictor of nutritional status because it represents BCM, the “working” portion of lean body mass.

The present study is a cross-sectional investigation of TBK values in healthy volunteers in seven age groups from 20 to 89 y. The purpose of the study is to show the dependence of body composition on age by using techniques unbiased by the body-composition changes of the aged. We also address the question of the extent of the depletion of BCM with age and its possible similarities to catabolic diseases. In vivo, neutron-inelastic-scattering measures were included to investigate the fat content of this population as a function of age and the quality of lean body mass, measured by its potassium content, throughout adult life.

SUBJECTS AND METHODS

Subjects

The study was conducted at the Jean Mayer US Department of Agriculture Human Nutrition Research Center (HNRC) on Aging at Tufts University by recruiting healthy, free-living white volunteers from the Boston area. Volunteers with a history of cardiac, hepatic, and renal disease; cognitive impairment; alcoholism; rheumatoid arthritis; or terminal illness were excluded from the study. Pregnant women were also excluded. One hundred eighty-eight volunteers, 96 females and 92 males, underwent the study protocol. Some volunteers > 65 y of age were receiving medication for hypertension (n = 16), gastrointestinal problems (n = 6), and glaucoma (n = 3). The baseline features of the subjects are presented in Table 1. A physical examination was performed to verify good health followed by screening for hematologic abnormalities. All subjects signed an informed consent form for participation in the study, which was approved by the Human Investigation Review Committee of Tufts University and New England Medical Center Hospitals.

Protocol

The volunteers came to the metabolic research unit of the HNRC for a 5-h visit. They had fasted overnight and after an examination of their vital signs, body height and weight were measured, with accuracy to 0.5 cm and 100 g, respectively. The following measurements were performed: 1) TBK by whole-body 40K gamma-ray counting and 2) total body fat by neutron inelastic scattering.

Description of the TBK whole-body measurement

The HNRC gamma ray whole-body counter was originally used for radioisotope absorption and retention studies (13). It was then modified—by changing the detector scanning speed and detection uniformity—to include TBK measurements. The whole-body counter measures the number of gamma rays resulting from the decay of the natural isotope 40K. Because 40K is present in a constant proportion (0.0118%) to the total mass of natural potassium, its gamma activity constitutes a measure of TBK. To measure the value of TBK precisely and accurately for a variety of volunteer body sizes, several technical issues had to be considered.

Background reduction

Because of its long half-life (1.28 × 109 y), 40K is one of the few radioactive elements in our solar system that is still present in detectable amounts and the only significant source of radioactivity occurring naturally in the human body. However, because of its presence in nature, measuring the potassium of a

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TABLE 1
Volunteer characteristics and mean body-composition values for normal females and males

<table>
<thead>
<tr>
<th>Age range by sex</th>
<th>n</th>
<th>Age (y)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>TBK (g)</th>
<th>TBK/height (g/cm)</th>
<th>TBK/weight (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>20-29 y</td>
<td>(n = 19)</td>
<td>25.3 ± 2.0</td>
<td>164.1 ± 4.6</td>
<td>61.6 ± 8.3</td>
<td>101.4 ± 10.2</td>
<td>0.62 ± 0.059</td>
<td>1.67 ± 0.22</td>
</tr>
<tr>
<td>30-39 y</td>
<td>(n = 13)</td>
<td>33.9 ± 2.8</td>
<td>164.0 ± 5.6</td>
<td>63.6 ± 13.7</td>
<td>98.7 ± 13.5</td>
<td>0.60 ± 0.071</td>
<td>1.59 ± 0.29</td>
</tr>
<tr>
<td>40-49 y</td>
<td>(n = 13)</td>
<td>46.2 ± 2.4</td>
<td>165.4 ± 7.3</td>
<td>69.2 ± 9.3</td>
<td>96.4 ± 8.1</td>
<td>0.58 ± 0.044</td>
<td>1.41 ± 0.18</td>
</tr>
<tr>
<td>50-59 y</td>
<td>(n = 10)</td>
<td>52.7 ± 2.8</td>
<td>163.1 ± 7.3</td>
<td>73.1 ± 16.1</td>
<td>95.8 ± 11.3</td>
<td>0.59 ± 0.063</td>
<td>1.35 ± 0.22</td>
</tr>
<tr>
<td>60-69 y</td>
<td>(n = 15)</td>
<td>65.9 ± 2.6</td>
<td>160.9 ± 4.8</td>
<td>63.0 ± 8.9</td>
<td>85.2 ± 9.6</td>
<td>0.53 ± 0.052</td>
<td>1.36 ± 0.12</td>
</tr>
<tr>
<td>70-79 y</td>
<td>(n = 12)</td>
<td>72.8 ± 2.5</td>
<td>156.7 ± 7.8</td>
<td>65.5 ± 11.7</td>
<td>79.8 ± 7.0</td>
<td>0.51 ± 0.046</td>
<td>1.24 ± 0.17</td>
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<tr>
<td>80-89 y</td>
<td>(n = 14)</td>
<td>83.6 ± 2.8</td>
<td>157.3 ± 5.8</td>
<td>58.3 ± 11.3</td>
<td>72.3 ± 9.6</td>
<td>0.46 ± 0.056</td>
<td>1.26 ± 0.18</td>
</tr>
<tr>
<td>Males</td>
<td></td>
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</tr>
<tr>
<td>20-29 y</td>
<td>(n = 14)</td>
<td>24.6 ± 2.3</td>
<td>179.8 ± 6.0</td>
<td>80.2 ± 7.8</td>
<td>164.5 ± 17.3</td>
<td>0.92 ± 0.092</td>
<td>2.06 ± 0.23</td>
</tr>
<tr>
<td>30-39 y</td>
<td>(n = 12)</td>
<td>33.8 ± 2.1</td>
<td>175.8 ± 8.1</td>
<td>77.1 ± 10.9</td>
<td>145.6 ± 20.6</td>
<td>0.85 ± 0.091</td>
<td>1.90 ± 0.16</td>
</tr>
<tr>
<td>40-49 y</td>
<td>(n = 10)</td>
<td>42.4 ± 2.1</td>
<td>176.8 ± 6.4</td>
<td>86.3 ± 6.7</td>
<td>148.3 ± 15.3</td>
<td>0.84 ± 0.086</td>
<td>1.72 ± 0.19</td>
</tr>
<tr>
<td>50-59 y</td>
<td>(n = 13)</td>
<td>55.9 ± 2.3</td>
<td>176.0 ± 8.2</td>
<td>88.0 ± 11.7</td>
<td>146.1 ± 12.9</td>
<td>0.83 ± 0.064</td>
<td>1.68 ± 0.17</td>
</tr>
<tr>
<td>60-69 y</td>
<td>(n = 14)</td>
<td>65.4 ± 2.7</td>
<td>173.6 ± 8.3</td>
<td>76.2 ± 12.1</td>
<td>128.2 ± 17.8</td>
<td>0.74 ± 0.088</td>
<td>1.70 ± 0.23</td>
</tr>
<tr>
<td>70-79 y</td>
<td>(n = 19)</td>
<td>73.8 ± 2.6</td>
<td>174.6 ± 6.7</td>
<td>78.0 ± 11.2</td>
<td>120.2 ± 11.5</td>
<td>0.69 ± 0.055</td>
<td>1.56 ± 0.16</td>
</tr>
<tr>
<td>80-89 y</td>
<td>(n = 10)</td>
<td>83.1 ± 2.9</td>
<td>167.2 ± 6.7</td>
<td>73.5 ± 9.5</td>
<td>106.8 ± 11.1</td>
<td>0.64 ± 0.048</td>
<td>1.46 ± 0.11</td>
</tr>
</tbody>
</table>

* * *
person by counting the $^{40}$K-emitted gamma rays requires isolation from environmental sources of $^{40}$K, which include soil, stone, concrete, and other persons. This is achieved at our facility by enclosing the volunteer and the gamma-ray detectors in a room made from 15-cm thick pre-1945 steel on all sides and lined with 3-mm lead shielding. This pre-World War II steel was chosen because it is free of nuclear fallout isotopes. It has served as an effective shielding, reducing the background counting from 2200 $\pm$ 800 to 200 $\pm$ 2 cpm/detector in the region of the $^{40}$K gamma-ray energy. The most important result, however, was that the background was found to be constant from measurement to measurement and from day to day, showing a random seasonal variation of $<0.8\%$. This indicates that the system is well protected from other common sources of radiation such as radioactive radon, which, because of its gas form and its affinity for clothing, has been a serious source of unpredictably varying background at other installations (14). Despite its observed stability, a separate background measurement was performed before and after each volunteer scan.

Sensitivity and uniformity of detection

The whole-body counter consists of two thallium-activated sodium iodide [NaI(Tl)] crystals (29 cm diameter $\times$ 10 cm) positioned vertically 39 cm above and 7 cm below a polyvinylchloride bed. A tracking system carries both crystals 1.91 m via a computer-operated, variable-speed stepping motor. An ideal whole-body counter would allow equal contribution to the $^{40}$K counts from any part of the body (15). In other words, we require that a small bottle of potassium chloride solution, positioned anywhere on the volunteer's bed, would yield the same number of counts despite the difference in the proximity of each point of the bed to the detectors. We compensate for this geometrical dependence of the efficiency of detection by using a variable-speed scan, which makes the detectors move faster when they are over the middle section of the body, resulting in uniformity along the axis of the scan. (A uniform-speed scan would have led to an amplified contribution from the middle section of the body.) To achieve uniformity of detection efficiency along the axis perpendicular to the scanning, two off-center measurements are taken, one over the left and one over the right half of the body, each scan lasting 20 min. The final measurement is the superposition of the data from the two scans. The volunteers stay in the shielded room for 40 min. The counting sensitivity for potassium was measured with an anthropomorphic phantom filled with a solution of potassium chloride containing 100.03 g natural K. The sensitivity of the system was 0.233 g K $\cdot$ $^{40}$K count$^{-1}$ $\cdot$ min$^{-1}$.

Body size independence

A portion of the gamma rays emitted in the body will be reabsorbed by tissue before they reach the detectors. This introduces a detection efficiency factor that depends on the thickness of the body. There are two approaches to correcting for body size. One is to scan a radioactive source under the volunteer and observe the attenuation of the photons recorded by the opposite detector because of the presence of the body. We chose to use the alternative approach, which is to calculate a correction for each volunteer based on four anthropometric thicknesses and the subject's height. Based on the anthropometric measurements, the body is divided into five segments of approximately elliptical cross section. The attenuation correction for each segment is calculated based on its thickness and the attenuation coefficient for 1.46-MeV gamma rays in tissue.

Accuracy, precision, and stability

Accuracy was estimated to be $\pm$ 5% on the basis of anthropomorphic phantoms filled with potassium chloride solutions of different concentrations (60, 100, and 190 g K). Precision was tested with anthropomorphic phantoms and repeated measurement of the same volunteer and was found to be $\pm$ 3%. Instrumental stability was monitored with a solid potassium chloride phantom, which was counted in the whole-body counter each day of operation in the scanning mode used for the volunteers. This phantom contained 3016 g KCl and was designed to provide a strong $^{40}$K signal so that fluctuations outside the small statistical error of gamma-ray counting could be detected. The variation of the instrument was found to be random with a CV of the solid potassium chloride phantom measurement of 0.6%, which was consistent with the expected statistical error for the gamma-ray counting.

Safety

The movement of the scanning detectors and the isolation of the volunteer for 40 min have been the two safety concerns. Two independent electronic systems were installed to check the speed and position of the detectors. One is connected to the computer that controls the motion of the detectors by driving the stepping motor. This system interrupts motion on request by the operator or by activation of safety position sensors. An independent secondary system of sensors would interrupt power to the scanning system in case of failure of the motion-control computer. The volunteer being measured was monitored by a cardiopulmonary resuscitation—trained operator via a closed-circuit television camera and an intercom system at all times.

Body fat measurements

The neutron-inelastic-scattering method was used for the measurement of total body fat. This method is based on the in vivo measurement of total body carbon (TBC) (16). Body fat and protein are the main contributors to TBC, whereas bone ash and carbohydrates contribute $<3\%$. Fat is calculated from TBC after the subtraction of the carbon contributions from protein, bone, and glycogen. Unlike models that evaluate body fat by subtracting lean body mass from body weight, the TBC technique is not sensitive to assumptions about the composition of lean tissue. The fast neutrons needed for the irradiation are produced by a miniature deuterium-tritium—pulsed neutron generator (8 kHz) from Sandia National Laboratories manufactured by Martin Marietta Specialty Components (Largo, FL) under a contract between the US Department of Agriculture and the US Department of Energy. The volunteer lies on a scanning bed that moves slowly over the neutron generator for a period of 24 min. During the scan, fast neutrons (kinetic energy = 14 MeV) from the neutron generator source produce characteristic gamma rays from the inelastic scattering of the neutrons off the $^{12}$C nuclei in the subject's body. The gamma rays are measured and analyzed by energy simultaneously with the irradiation for the determination of TBC. The radiation
exposure to the patient due to the neutrons is 0.10 mSv (10 mRem), much less than that from a single chest X-ray.

The carbon-nitrogen-calcium model for body fat assessment

Body fat is calculated from TBC, protein, and bone ash by using the following model (adapted from reference 16):

\[ C_f = TBC - (C_p + C_g + C_b) \]  

where \( C_f \), \( C_p \), \( C_g \), and \( C_b \) are carbon in fat, protein, glycogen, and bone ash, respectively. Use of the stoichiometry for each contributor produces the following:

\[ C_f = TBC - [(TBN \times 3.31) + (TBN \times 0.12) + (TBCa \times 0.05)] \]  

Total body nitrogen (TBN) is used to predict both protein and glycogen. Total body calcium (TBCa) is used to derive bone ash.

For the application of this model, TBC, TBN, and TBCa are measured by neutron inelastic scattering (16), prompt-gamma neutron activation (17, 18), and delayed neutron activation (19), respectively.

The carbon-potassium model for body fat assessment

We showed in a previous publication (16) that the bone ash contribution to TBC is minimal and can be omitted. We have also shown that, for calculating fat, TBK can be used to predict TBN because of a favorable error propagation. An error of 9% in predicting TBN results in a small increase in the total fat content uncertainty, ranging between 1.2 and 1.6 percentage points.

To validate the carbon-potassium model against the standard carbon-nitrogen-calcium method, we used our published data from Brookhaven (16), for which 13 subjects were measured for fat, protein, carbon, nitrogen, and calcium by using the techniques described above.

We calculated percentage fat (%Fat2) using not the measured nitrogen values but the potassium-predicted ones. The prediction equations of Ellis et al (5) were used as follows:

\[ \text{TBNp (g) = 12.95 \times \text{TBK (g)} + 151.7 \text{ for females} } \]  

\[ \text{TBNp (g) = 10.15 \times \text{TBK (g)} + 405.6 \text{ for males} } \]  

where TBNp is the predicted nitrogen value. Ellis et al reported that the average uncertainty for the prediction was 127 g for females and 119 g for males \( (r = 0.79 \) and 0.87, respectively).

We compared %Fat2 against %Fat1 (derived by using the original carbon-nitrogen-calcium model). The two methods agreed typically within one percentage point, with a maximum error of 1.3% (Figure 1).

Given the uncertainties associated with the in vivo measurement of body nitrogen by prompt-gamma neutron activation, and the significant dependence of its measurement error on the body thickness (18, 20), we concluded that the simplified carbon-potassium model for fat offers a reasonable alternative at a fraction of the radiation exposure (0.10 mSv for the carbon-potassium compared with 3.80 mSv for the carbon-nitrogen-calcium model).

The quality of TBC measurements is not sensitive to body thickness because of the penetration of the fast neutrons in tissue and the energy of the measured carbon gamma ray (4.43 MeV). The thickness response of the TBC measurements has been examined by Monte Carlo simulation (21).

The overall error for estimating fat from TBK is 4.0%. The technical details of the equipment and the TBK model were described elsewhere (16, 21–23).

Statistical analysis

Data are presented in Table 1 as means ± SDs by decade of age so that comparison with earlier reports can be direct. The statistical analysis, however, was performed with individual values, not decade averages. SYSTAT for Windows, version 6 (SYSTAT, Inc, Evanston, IL) was used for the linear and quadratic regressions. We used inverse-regression analysis to calculate the 95% CIs for maximum life span (24).

RESULTS

The TBK measurements are presented in Table 1 by decade of age. We observed a systematic loss of TBK with age \( (P \leq 0.001) \) described by the following quadratic equations (Figure 2):

\[ \text{TBK (g) = 100.2 + 0.214 \times \text{age} - 0.00658} \]  

\[ \times \text{(age)}^2 \text{ for females} \quad (r = 0.729, P \leq 0.001) \]  

\[ \text{TBK (g) = 164.5 + 0.0167 \times \text{age} - 0.00843} \times \text{(age)}^2 \text{ for males} \quad (r = 0.760, P \leq 0.001) \]  

The same data are also presented as g TBK/cm body height by decade of age (Table 1). The main characteristics of the data are preserved when body frame size is taken into consideration \( (P \leq 0.001) \) as follows:

\[ \text{TBK/height (g/cm) = [612.5 + 0.993} \times \text{age} - 0.0334 \times \text{(age)}^2]/1000} \]  

for females \( (r = 0.614, P \leq 0.001) \)
Our TBK/weight equations:

\[
TBK\text{/weight (g/kg)} = 1.81 - 0.00720 \times \text{age for females} \tag{9}
\]

\[
TBK\text{/weight (g/kg)} = 2.23 - 0.00916 \times \text{age for males} \tag{10}
\]

Our results show that TBK content declined at a rate of 7.20 ± 1.00 mg K \cdot kg body \text{wt}^{-1} \cdot \text{y}^{-1} for females (r = 0.601, P ≤ 0.001) and 9.16 ± 0.96 mg K \cdot kg body \text{wt}^{-1} \cdot \text{y}^{-1} for males (r = 0.710, P ≤ 0.001).

Most of the volunteers (66 females and 70 males) were also measured for body fat by neutron inelastic scattering. The results are presented in Table 2. We observed a systematic increase of body fat content up to the fifth decade of life for women, and throughout the age range for men.

**DISCUSSION**

**The decline of TBK with age**

The observed relation between TBK and age is consistent with earlier longitudinal data reported by Flynn et al (25), who monitored TBK loss in an 18-y-long study. The results are also consistent with earlier longitudinal observations by Forbes and Reina (26) and cross-sectional data reported by Pierson et al (27) and Ellis et al (5), who reported TBK data by decade of age using the whole-body counter at Brookhaven National Laboratory and a TBK counting technique and volunteer population similar to ours. We found agreement within sampling error for each age group between our data and that from Brookhaven with the exception of our oldest group, for which comparable Brookhaven data were not available.

Our data support the hypothesis that there is a systematic and continuous loss of BCM with age, throughout adult life. To investigate the age dependence of TBK, we defined as total body potassium content the TBK per body weight, and present the body potassium content as the ratio of TBK content to its maximum value, which corresponds to that of the youngest group of our subjects. The decline of TBK content as a function of age for adult life in a way that is independent of body size and absolute TBK value is shown in Figure 3. All data are presented as a percentage of the TBK content at age 25 y. The resulting plot is consistent with a linear decline, which fits the data for both males and females. Our data show a linear decline in TBK content with age according to the following relation:

\[
TBK \text{ content (})\%\text{)} = 108.28 - 0.438 \times \text{age (y)} \tag{11}
\]
Kotler et al (28) showed that in the case of severe, catabolic end-stage acquired immunodeficiency syndrome, the patients cannot sustain a loss of > 40% of their body potassium. Similar data were obtained in studies of starvation (29). We can interpret this observation as the minimum amount of cell mass that is necessary to maintain the basic metabolic mechanisms to sustain life. If we extend the line of Figure 3 to the point of 60% (which represents a 40% TBK loss), we would come up with age 110 y (95% CI: 101.3, 122.4), which would define the theoretical life span limit based on this simplified TBK content model and our population. This result is consistent with other methodologies that have calculated maximal human life span, which predict 110–120 y as the upper limit (30, 31).

Body fat content and aging

Unlike the age dependence of TBK, we found a difference between male and female volunteers with respect to change in fat with age. We observed a systematic increase of body fat content up to the fifth decade of life for women, and throughout the age range for men (Table 2). Our findings are consistent with bioelectrical impedance analysis data used to predict the fat content of 2032 adult participants in the Framingham Offspring Study (32), as well as with hydrodensitometry measurements of nonobese adults (33). Other investigators using a variety of methods have concluded that, in cross-sectional observations, body fat content increases monotonically with age for both sexes (34). The explanation for the different observations may be the recruitment methods used to conduct each study. For the older subjects, high body fat content becomes associated with poor health, mobility, and survival and most of these subjects are not able to be recruited from the healthy, free-living population.

The quality of lean tissue

We used our TBC-derived fat content measurements to calculate fat-free mass (FFM) by subtraction from body weight. The TBC model uses no assumptions about the chemical composition of lean body mass, which will vary with age. It is, therefore, a method that does not carry an intrinsic age-dependent bias and is used to estimate FFM independently of the TBK values or of the hydration level of lean tissue. The portion of the FFM occupied by the oxygen-consuming metabolizing cells can be used as a measure of quality of lean tissue. The age dependence of the potassium content of lean body mass is shown in Figure 4. Two characteristics are immediately apparent: the drop in TBK:FFM with age and the large variation of this ratio within each age group. The variation in TBK:FFM indicates that TBK alone may be a poor predictor of the lean body mass of an individual unless age- and sex-dependent equations are used. Potassium is, however, the most important ingredient of lean body mass, the portion responsible for the metabolic function of the body, and an indirect indicator of muscle mass.

Potassium depletion with age can be explained by loss of cell mass because of insufficient replacement of cells, or because of a change in intracellular potassium concentration. We expect cell depletion to be the dominant factor. For example, imaging studies showing the effect of age on the cross section of the muscle measured at mid thigh by magnetic resonance imaging or computerized tomography scans (35, 36) are consistent with loss of cells with age. A change in intracellular potassium, on the other hand, requires a change in the function of the cellular membrane with age. Jeejeebhoy (37) showed such changes in the sodium-potassium pump in malnutrition and in animal experiments with starvation (38). The participation of such a mechanism in aging has yet to be investigated.

This type of investigation into the mechanisms of TBK loss with age has some historical similarities to osteoporosis research. The investigation of osteoporosis was aided by the development of in vivo techniques for measuring TBCa with neutron activation, initially, and total bone mineral with X-rays more recently. Like TBK, a single total-body element measurement (TBCa) provided information on risk of developing osteoporosis. In the case of patient risk evaluation, the rate of loss is usually more important than the absolute value. In osteoporosis, the benefit of entering menopause with a relatively high baseline of bone mineral was discovered and specific nutritional and lifestyle guidelines were developed. Even if the rate of TBK depletion is continuous and sex independent, one could expect that higher potassium concentrations due to increased lean mass would be beneficial later in life by allowing for more TBK loss. We expect the specific public health guidelines regarding the maintenance of lean body mass to be derived from the understanding of the detailed mechanisms of sarcopenia and its relation to function and quality of life of the elderly.

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