

*Chapter 14*

**THE UBIQUITY OF BACKGROUND RADIATION  
AND THE CLINICAL UTILITY OF NATURALLY  
OCCURRING POTASSIUM-40 IN HUMAN BODY**

*Lucian Wielopolski<sup>1\*</sup>, Pierre K. Asselin<sup>2</sup>, Lisa M. Ramirez<sup>2</sup>  
and William A. Bauman<sup>2#</sup>*

<sup>1</sup>Brookhaven National Laboratory, Environmental Sciences Department, Upton, NY, US

<sup>2</sup>James J. Peters VA Medical Center, Bronx, NY, US

**ABSTRACT**

The commonly accepted notion that any dose of radiation is carcinogenic is questionable in light of our current appreciation of the evolution of our planet and the life that has quite successfully evolved upon it. The earth was born in an abundant sea of radiation. Thus, the premise of the linear no-threshold hypothesis that extrapolates the risk from radiation exposure at higher levels to that at lower levels in a linear fashion without recognizing a lower limit of risk is of questionable scientific merit and, in our opinion, requires appropriate revision. The presence of natural background radiation and its abundance in the human body is reviewed. One of the naturally occurring radioisotopes in the human body, <sup>40</sup>K, is discussed as a useful marker of intracellular space of the brain and of muscle mass of the limbs, which measurements may be of relevance for clinical diagnostic purposes.

**INTRODUCTION**

The linear no-threshold (LNT) hypothesis estimates the risk to humans resulting from low-level exposure (LLE) to radiation. The LNT is a linear extrapolation without a threshold of the risk at LLE derived from data acquired at higher exposure levels. In the late 1940s, a

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\* Brookhaven National Laboratory, Environmental Sciences Department, Bldg 490D, Upton, N. Y. 11961.  
E-mail address: [lwielo@bnl.gov](mailto:lwielo@bnl.gov).

# James J. Peters V. A. Medical Center, 130 W. Kingsbridge Rd. Room 7A-13 Bronx, N. Y. 10468.

transition started from the tolerance dose model to the LNT concept as the conventional basis for societal administrative approaches to radiation protection. This concept was promoted by the first report of the United Nations Scientific Committee on the Effects of Radiation and, subsequently, it was codified in the first report by the newly created US Federal Radiation Council (FRC) [1] with absolutely no scientific evidence to support its adoption. The administrative decision to adopt the LNT as the guiding force for protection from harmful radiation was guided by its mathematical simplicity and its perceived conservatism in its judicious and prudent representation of an upper limit for risk in the low-dose region; the administrative origin of this decision has largely been forgotten. The LNT assertion that “any radiation dose, no matter how small, can cause cancer” has been accepted in some government oversight bodies, as well as the lay literature, as “a matter of fact.” This notion has gained legitimacy as a consequence of the deep desire to err on the side of caution by using more conservative estimates of the risk, but it lacks scientific rigor. Ever since its rise to prominence, controversy has surrounded the issue of linearity of radiation risk because scientists were accustomed to the ‘S’ toxicological curves, and the concept of no-threshold appeared to run contrary to experience. The concept of no-threshold level for radiation exposure is troublesome because the energy required to damage DNA, and thus to surpass the threshold for carcinogenic radiation, is known to be considerable. This implies that at least one particle hit occurred to the DNA, and the energy deposited from this single hit would be at a high dose since it would have occupied a very small volume, i.e., high energy per unit volume. Therefore, the assumption that an ever decreasing dose due to a single energy transfer in an ever increasing mass is inevitably carcinogenic should be, by logical analysis, considered almost ludicrous.

Furthermore, because of the adaptive biological process of genomic repair, there is strong evidence to suggest a threshold value for radiation exposure exists, below which the initiation of cancer is highly unlikely to occur despite even a direct radiation hit to the chromosome because of cellular capability to repair limited chromosomal damage. During the last two to three decades, scientists have increasingly questioned the validity of the LNT to serve as the working model used to regulate the potential health effects of low-level radiation, accompanied by its inherent enormous financial burden to society [2, 3, 4]. A discussion of the ever-present background radiation and its potential diagnostic utility is presented.

**Table 1. Activities of primordial radionuclides in one kg of rock, except radon gas present in the atmosphere [5]**

Nuclide	Symbol	Half-life (yr)	Concentration (Bq/kg rock)*
Uranium 235	<sup>235</sup> U	7.04 x 10 <sup>8</sup>	0.01
Uranium 238	<sup>238</sup> U	4.47 x 10 <sup>9</sup>	30
Thorium 232	<sup>232</sup> Th	1.41 x 10 <sup>10</sup>	41
Radium 226	<sup>226</sup> Ra	1.60 x 10 <sup>3</sup>	16
Radon 222	<sup>222</sup> Rn	3.82 (days)	0.6 (Bq/m <sup>3</sup> )
Potassium 40	<sup>40</sup> K	1.26 x 10 <sup>9</sup>	630
Rubidium 87	<sup>87</sup> Ru	4.80 x 10 <sup>10</sup>	70

\* 1 Bq = 27 pCi.

**Table 2. Radionuclides produced in the atmosphere by neutron capture [5]**

Radionuclide	Half-live	Main Radiation (MeV)	Target Nuclide
<sup>10</sup> Be	1.6 x 10 <sup>6</sup> y	β 0.55	N, O
<sup>26</sup> Al	7.2 x 10 <sup>5</sup> y	β <sup>+</sup> 1.17; γ 1.81, 0.51	Ar
<sup>35</sup> Cl	3.0 x 10 <sup>5</sup> y	β 0.71	Ar
<sup>80</sup> Kr	2.1 x 10 <sup>5</sup> y	K x-ray	Kr
<sup>14</sup> C	5.7 x 10 <sup>3</sup> y	β 0.16	N, O
<sup>32</sup> Si	3.5 x 10 <sup>2</sup> y	β 0.21	Ar
<sup>39</sup> Ar	2.7 x 10 <sup>2</sup> y	β 0.56	Ar
<sup>3</sup> H	12.33 y	β 0.018	N, O
<sup>22</sup> Na	2.60 y	β <sup>+</sup> 0.54, 1.82; γ 1.27, 0.51	Ar
<sup>35</sup> S	87.4 d	β 0.17	Ar
<sup>7</sup> Be	53.3 d	E.C.; γ 0.48	N,O
<sup>37</sup> Ar	35.0 d	K x-ray	Ar
<sup>33</sup> P	25.3 d	β 0.25	Ar
<sup>32</sup> P	14.3 d	β 1.71	Ar
<sup>28</sup> Mg	21.0 hr	β 0.46; γ 1.35, 0.31	Ar
<sup>24</sup> Na	15.0 hr	β 1.39; γ 1.37, 2.75	Ar
<sup>38</sup> S	2.83 hr	β 3.00; γ 1.88, 1.6	Ar
<sup>31</sup> Si	2.62 hr	β 1.48; γ 1.26	Ar
<sup>18</sup> F	1.83 hr	β <sup>+</sup> 0.63; γ 0.51	Ar
<sup>39</sup> Cl	56.2 min	β 1.91 to 3.45; γ, 1.27, 1.52	Ar
<sup>38</sup> Cl	37.3 min	β 4.91; γ 1.50, 2.17	Ar
<sup>34m</sup> Cl	32.0 min	β <sup>+</sup> 2.45; e <sup>-</sup> 0.14; γ 1.17, 2.12, 3.3	Ar

## BACKGROUND RADIATION

Our world is radioactive, and it has been so since its inception. Over one hundred radioactive natural and man-made elements can be found in the environment. These “hot” elements are located in the soil, atmosphere, water, and, thus, in everything else inanimate or animate. The sources of natural radioactivity in the environment may be categorized as *primordial*, arising early in creation before the earth was formed, and *cosmogenic*, resulting from cosmic radiation interacting with elements in the atmosphere and on earth; *anthropogenic* radioactivity is a consequence of human activity during the past 150 years [5].

### Primordial

There are several dozen naturally occurring radionuclides with half-lives near or longer than the estimated age of the earth, ~4.5 10<sup>9</sup> years. These are categorized into series of radionuclides, with the list headed by <sup>235</sup>U, <sup>238</sup>U, and <sup>232</sup>Th, elements that decay into stable Pb isotopes. The Th series is responsible for one of the progenies, <sup>222</sup>Rn, a noble radon gas that is inhaled by humans. There are seventeen more radionuclides in the earth’s crust with half-lives longer than the age of our planet; generally, these additional radionuclides are encountered in very low abundance and activity, except for those of <sup>40</sup>K and <sup>87</sup>Rb. The concentration of the

various radionuclides and their average activities in rocks are summarized (Table 1). As the rocks weather and wear down, they undergo a geo- chemical- bio-process that causes the radionuclides to be transferred from rock into the soil, and then from the soil to be incorporated into the food chain.

## Cosmogenic

Cosmogenic radionuclides are produced by the bombardment of cosmic radiation of very high energy particles undergoing spallation with elements in the upper- and lower-atmosphere; particles on the earth may also have become radioactive by the same process of collision with cosmic radiation. Typically the cosmogenic radionuclides are shorter lived than those of primordial origin. Many of the radionuclides resulting from neutron capture by the atmosphere gases are;  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{80}\text{Kr}$ ,  $^{14}\text{C}$ ,  $^{32}\text{Si}$ ,  $^{39}\text{Ar}$ ,  $^{22}\text{Na}$ ,  $^{35}\text{S}$ ,  $^{37}\text{Ar}$ ,  $^{33}\text{P}$ ,  $^{32}\text{P}$ ,  $^{28}\text{Mg}$ ,  $^3\text{H}$ ,  $^{24}\text{Na}$ ,  $^{38}\text{S}$ ,  $^{31}\text{Si}$ ,  $^{18}\text{F}$ ,  $^{39}\text{Cl}$ ,  $^{38}\text{Cl}$ , and  $^{34\text{m}}\text{Cl}$ . These are summarized in descending order of half-lives and the main radiations emitted (Table 2). The elements carbon and hydrogen, with their radioactive isotopes  $^{14}\text{C}$  and  $^3\text{H}$ , are an integral part of the elements that compose the human body.

The cosmogenic- and terrestrial-radionuclides, inclusive of radioactive radon and those internal to the human body, i.e.,  $^{40}\text{K}$ ,  $^{14}\text{C}$ ,  $^3\text{H}$  and  $^{87}\text{Ru}$ , deliver radiation doses at approximate levels of 25, 29, 200 and 40 mrem/y, respectively. Consequently, the continuous exposure to background radiation to man averages, approximately, 300 mrem/year. Large fluctuations in radiation exposure, by a factor of 10 or more, can be encountered depending on geographical location. In “hot” areas, such as around Ramsar, Iran, background levels or radiation have been observed to be 200-times higher than that found in other geographical locations [6].

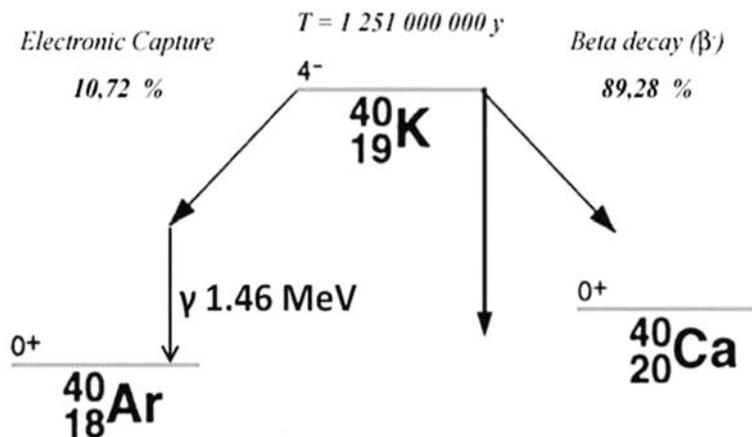
## Radiation in Human Body

As previously discussed, the primordial and cosmogenic radionuclides mix in the soil and are ingested through the food chain and other radionuclides are inhaled or absorbed through the skin. The key radionuclides and their activities in human body are summarized (Table 3). The major contributors to the radiation dose are as followed:  $^{40}\text{K}$ ,  $^{14}\text{C}$ ,  $^3\text{H}$  and  $^{87}\text{Rb}$ . About half of the total 3700 Bq of radioactive  $^{14}\text{C}$  found in the human body is located in the genetic information (i.e., DNA), which is essentially segregated in about half of the area of the cell [7]. Tritium is in equilibrium with body water and, thus, uniformly distributed throughout the body’s fluid compartments. About 98% of  $^{40}\text{K}$  is located intracellular, and  $^{87}\text{Rb}$  is located in the skin, without having a clearly identified function for this element.

There are about 8,000 disintegrations per second (dis/sec) in the human body solely due to internal radiation per se, which calculates to  $2.5 \times 10^{11}$  dis/y. Therefore, the entire US population is responsible for  $7.5 \times 10^{19}$  dis/year, and the world’s population is responsible for  $1.5 \times 10^{21}$  dis/y. As such, “endogenous” disintegrations calculate to be an exceptionally large number. Thus, it behooves us to recognize the obvious— that is, humanity is in harmony with and prospers despite these naturally occurring radioactive events.

**Table 3. Activities of radionuclides in the human body**

Radioactive Isotope	Half Life (years)	Isotope Mass in the Body (grams)	Element Mass in the Body (grams)	Activity within the Body (dis/sec)
Potassium 40	$1.26 \times 10^9$	0.0165	140	4,340
Carbon 14	5,730	$1.6 \times 10^{-8}$	16,000	3,080
Rubidium 87	$4.9 \times 10^{10}$	$0.19 \times 10^0$	0.7	600
Lead 210	22.3	$5.4 \times 10^{-10}$	0.12	15
Tritium ( $^3\text{H}$ )	12.43	$2 \times 10^{-14}$	7,000	7
Uranium 238	$4.46 \times 10^9$	$1 \times 10^{-4}$	$1 \times 10^{-4}$	3 - 5
Radium 228	5.76	$4.6 \times 10^{-14}$	$3.6 \times 10^{-11}$	5
Radium 226	1,620	$3.6 \times 10^{-11}$	$3.6 \times 10^{-11}$	3
Total				~8000

Figure 1. Schematic representation of  $^{40}\text{K}$  decay.**Table 4. Representative multi-component models at the five levels of body composition [11]**

Level	Body Composition Model	Number of Components
Atomic	BM=H+O+N+C+Na+K+Cl+P+Ca+Mg+S	11
Molecular	BM=FM+TBW+TBPro+Mo+Ms+CHO	6
	BM=FM+TBW+TBPro+M	4
	BM=FM+TBW+non-fat solids	3
	BM=FM+Mo+residual	3
	BM=FM+FFM	2
Cellular	BM=Cells+ECF+ECS	3
	BM=FM+BCM+ECF+ECS	4
Tissue-Organ	BW=AT+SM+bone+visceral organs+other tissues	5
Whole-Body	BW=head+trunk+appendages	3

Note: AT = adipose tissue, BCM = body cell mass, BM = body mass, CHO = carbohydrates, ECF = extracellular fluid, ECS = extracellular solids, FFM = fat free mass, FM = fat mass, M = mineral, Mo = bone mineral, Ms = soft tissue mineral, SM = skeletal muscle, TBPro = total body protein, TBW = total body water.



Figure 2. Whole body counter with  $^{32}\text{NaI}$  (Tl) detectors located in a low background room.

## THE PHYSICAL PROPERTIES OF K

Radioactivity plays a vital role in science, industry, and medicine. Radio-tracers have several diverse applications such as: in industrial gadgets utilizing manmade radiation sources for monitoring purposes; in radioimmunoassay to detect endogenous and exogenous hormones, drugs, biological molecules (i.e., cyclic AMP), and infectious agents; in imaging modalities; and in radiotherapy to treat cancer. Some elements in the human body that can be measured by exposing the whole body to neutron activation are C, N, Na, Cl, Ca, and Al, as well as other elements of clinical or research interest. One of the most prevalent natural radioisotopes found in the human body is  $^{40}\text{K}$ , which has favorable physical characteristics for clinical diagnostics. There are three isotopes of the element K which are distributed in isotopic form as followed: 93.26% as  $^{39}\text{K}$ , 6.73% as  $^{41}\text{K}$  and 0.0117% as  $^{40}\text{K}$ .  $^{40}\text{K}$  is an excellent measure of the total K in the body due to its extremely long half-life ( $1.26 \times 10^9$  years) and its being in equilibrium with the body's total K pool. The multi-modal decay model of  $^{40}\text{K}$  is depicted (Figure 1). In this model,  $^{40}\text{K}$  decay occurs by beta decay (89.3%) with a maximum energy of 1.31 MeV, or electron capture (10.72%) and gamma-ray production with energy of 1.461 MeV. Thus, one gram of  $^{40}\text{K}$  will emit  $\sim 200$  gamma-rays per minute [8, 9], and in conjunction with its biological intracellular residence, makes this isotope of K ideally suited for clinical diagnostic purposes.

## TOTAL BODY K

The composition of the human body can be measured by various organizational levels: atomic, molecular, cellular and tissue-organ [11, 12], which are then divided into different compartments (Table 4). At the atomic level, K is a critical element because it is needed for the proper functioning of all cells, tissues, and organs in all living creatures. It is also an electrolyte, and in association with other electrolytes (i.e., sodium, chloride, calcium, and magnesium), involved in electrical signaling and conductance in nerves, as well as other function in various body tissues. Potassium is crucial to cardiac function and plays a key role in skeletal and smooth muscle contraction, and thus essential for digestive and muscular function. All foods, to a various degree, contain potassium, including all meats, and to

varying degrees, many fruits, vegetables, and legumes. Dairy products also are sources of potassium. On average, the body's K compartment is 140 g in an adult male and 120 g in an adult female [10].

Due to the aforementioned radioactive properties of  $^{40}\text{K}$ , it is possible to readily measure total body potassium (TBK) using whole body counters (WBC). These systems contain multiple NaI (Tl) detectors, which have appropriate energy resolution in order to limit interference from other natural background isotopes; WBCs are usually located in shielded rooms to lower background radiation. A WBC with 32 NaI detectors, operated at Brookhaven National Laboratory is shown (Figure 2). The gamma-ray spectra acquired with a WBC are analyzed using various methods. One method that produces minimal error propagation uses library least-squares method, which will fit the entire elemental spectra to a measured spectrum [13].

Elemental potassium is a dominant cation that resides predominantly intracellular (>98%) [14], with about 84 g (60%) located in the skeletal muscle (SM), and the remainder distributed unevenly among the visceral organs [15, 10]. SM is the largest organ in the human body and is actively involved in energy metabolism and multiple biochemical and physiological processes. SM is often adversely affected by disease processes and/or inactivity that are associated with catabolism (i.e., increased total body nitrogen loss), inevitably resulting in sarcopenia [16]. A loss of 40% of SM significantly increases the risk of mortality. Thus, an accurate determination of the SM mass is of clinical relevance, as well as of tremendous interest to researchers of body composition. Although strides have been made in assessing SM, it still remains a difficult body component to assess quantitatively *in vivo*. The situation is made more difficult by our limited knowledge of the SM distribution in healthy adults [17].

The advantages and drawbacks of several methods, such as computerized tomography (CT), magnetic resonance imaging (MRI), dual-energy X-ray absorptiometry (DXA), and TBK were investigated by Lee and associates; they concluded that TBK is preferable to other models because it is a direct measure, but the instrumentation is prohibitively expensive and generally unavailable [18]. The advantage TBK has over other modalities is that K, due to its physical characteristics, is the only element in the human body that can be determined non-invasively in completely passive ways; its measurement is also not predicated on certain assumptions that can be variable from person-to-person, such as the hydration constant. Measuring TBK by WBC is widely recognized as the best indicator of the intracellular compartment, i.e., the body cell mass. Wang and colleagues, in an attempt to derive better estimates of SM, have also proposed a model based on TBK [19]. Not unexpectedly, the value of serum K is not a reliable marker of changes in the whole body K level [23].

The simplicity of the measurement of TBK, and its long history of being employed in nutritional research, has contributed to the quantification of TBK compared with the myriad other published body indexes. However, it should be re-emphasized that TBK is not exclusively a measure of K in the SM because the remaining 40% of body K is distributed among smooth muscle groups and the visceral organs. Because changes in TBK represent the total body's integrated response to disease processes or stress or inactivity, the small regional changes in the K content may not be possible to detect because they may be overshadowed by the overall changes, or lack thereof, in the remainder of the body [20].

## PARTIAL BODY K

In an effort to investigate regional changes, dedicated partial body K (PBK) counters have been developed. Two prevailing hurdles are inherent to the design of PBK systems: isolating the region of interest and designing appropriate shielding to reduce background K radiation. Three such systems have been developed to date by us to monitor K in the brain, upper extremities, and lower extremities.

### K in the Brain

Multiple sclerosis (MS) is a neurological disease which affects the central nervous system (CNS) where the earliest detectable finding is an increase in brain edema and inflammation. Recent studies suggest that brain regions with the highest water content are at increased risk for future development of MS lesions [21]. Although CNS edema is known to occur in MS, and such regional brain swelling reflects new disease activity, the proportion of intracellular to extracellular edema is entirely unknown. The precise and reproducible determination of this ratio would be anticipated to provide new insight into the MS disease processes. Because conventional neuroimaging methods cannot assess intracellular water, an approach using whole body composition studies was adapted for this purpose. K, being about 98% intracellular, it is recognized as the best estimate of body cell mass (BCM) [22].

Brain parenchyma may be conceptualized as being composed of three distinct fluid-filled compartments: a vascular space (i.e., blood vessels), an interstitial space, and an intracellular space (i.e., neurons and supporting cellular elements). About 80% by weight of the normal brain is water, of which only about 20% is extracellular. The most abundant aqueous cations in the brain are sodium, which is concentrated in extracellular space, and potassium, which is concentrated in the intracellular space. When cerebral edema occurs, it has not been possible to assess the proportions of extracellular (i.e., vasogenic) and intracellular (i.e., cytotoxic) edema by any modality. Since K is concentrated within intracellular space, an assumption can be made that any increases in fluid would correspond to an increase in K in order to maintain cell membrane potential. Thus, measurement of K in the brain could potentially be used as a marker to determine changes in intracellular fluid, thus providing an indication of cytotoxic edema.

**Table 5. Determination of K in the brain using a PBK system**

		Measured Brain K (g K $\pm$ SD%)	Reference Brain K (g K)
Male	1	4.94 $\pm$ 5	4.2
	2	4.22 $\pm$ 9	
	3	4.81 $\pm$ 6	
	Average	4.81 $\pm$ 11	
Female	1	4.13 $\pm$ 8	3.6
	2	3.83 $\pm$ 8	
	Average	3.98 $\pm$ 5	



Figure 3. A PBK system for the measurement of K in an arm.

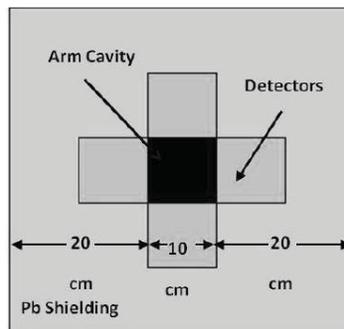


Figure 4. Cross configuration of the NaI detectors and the arm cavity.

A specialized PBK system was designed for brain that demonstrated the feasibility of measurement of K in brain, when the background K has been considerably reduced [24, 25]. This system was designed with NaI detectors embedded in shielding material that formed a cavity into which the head can be inserted. Calibration was performed using spherical phantoms filled with water and a known quantity of KCl, providing a within-system error of about 5-8%. The measurement of brain PBK in 5 subjects (3 males and 2 females) are presented (Table 5), and the values obtained are comparable to those for the brain in reference man and women.

### K in the Arms

SM is a critical organ but quite difficult to monitor for measurement of regional mass. Obviously, a method offering direct and more accurate estimate of the arm SM would undoubtedly be beneficial in providing clinical findings that could be related to muscle mass, strength and function, as well as the need to improve these parameter, if possible. Patients with chronic renal failure (CRF) who are undergoing dialysis become catabolic and lose SM.

A system designed for K measurement in the arms (Figure 3) and four detectors arrangement with the arm cavity (Figure 4) was constructed and tested on normal subjects, adult patients with CRF, and children [26]. The comparison of arm K and TBK measurements obtained in the same subjects demonstrated that both systems were complementary to each

other. The unique and distinct advantages of the PBK system enabled novel approaches for the development of new body composition models and permitted verification of existing models in compartmental analysis. The mean arm value of 7.97g K, obtained by PBK measurement of the arm in 58 males, was within the range of 7.6-8.4 g K reported in reference man [27]. The lower mean arm value of 5.32 g K obtained in 87 females was comparable to 4.2 g K obtained by regional lean mass equivalent performed by DXA scan. It was also observed that increase in arm K occurred at a lower rate than that of the whole body [28], which was hypothesized to be due to the multiplicity of body compartments that contain K determined by WBC (i.e., skeletal and smooth muscle, visceral organs, and other fat-free mass compartments), whereas arm PBK was predominantly a measure of skeletal muscle mass.

### **K in the Legs**

One of the untoward consequences of acute spinal cord injury (SCI) includes an unbridled catabolism, resulting in significant loss of sublesional SM due to paralysis and immobilization, regardless of nutritional intake. However, muscle loss above the lesion also occurs due to the stress of acute SCI, associated traumatic injuries and infection, as well as generalized disuse from immobilization after the acute traumatic event. The extent of muscle loss following the traumatic event may be a determination of the length of time required for rehabilitation—that is, the greater the atrophy of the remaining innervated muscle mass, the longer the recovery process. There is limited knowledge of the changes in the soft-tissue mass, which consists of muscle and fat tissue, immediately after the traumatic event. Investigators have studied patients subacutely after SCI (29, 30), with no studies reported that have captured patients within the first several days to weeks after injury due to the difficulty in obtaining sophisticated imaging modalities, such as DXA, computed tomography or magnetic resonance imaging. However, clinical observation and extrapolation from prior studies strongly suggest that there may be substantial and rapid losses in muscle tissue over the initial weeks to months following acute injury. Thus, undoubtedly, a more quantitative, comprehensive knowledge of the amount and rate of muscle tissue loss following acute SCI would be beneficial in accurately documenting the rate of SM loss in the extremities, and then being poised to design and test treatment strategies to preserve supralésional and/or possibly sublesional muscle mass. As previously discussed,  $^{40}\text{K}$  measurement is a very good indicator of SM and of intracellular water. To this end, a specially designed PBK system to measure regional K in the legs was constructed. The PBK system was mounted on a cart with wheels to enable it to be wheeled, at least in principle in the future, to the bedside of an acutely injured patient for leg  $^{40}\text{K}$  measurement early after SCI, and then serially over time. The PBK system is shown (Figure 5).

In a preliminary report, this PBK system demonstrated the suitability of measuring SM of the legs in two cohorts: 10 healthy controls and 10 persons with chronic SCI [31]. This study was repeated recently with a modified system which is lighter, more maneuverable, and has upgraded electronics. Similar to the previous study, two cohorts with 10 subjects in each group were assessed at four separate time points.

Within a two week time period, every individual was measured twice on their first visit and twice on their second visit. A plot of the net counts from  $^{40}\text{K}$  observed in the legs of each subject is shown (Figure 6).

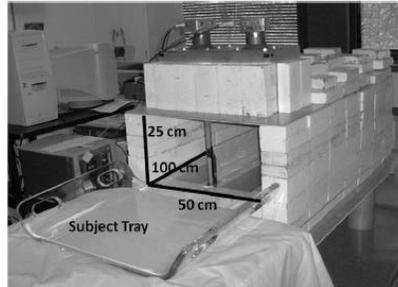


Figure 5. A PBK system for the measurement of K in the legs.

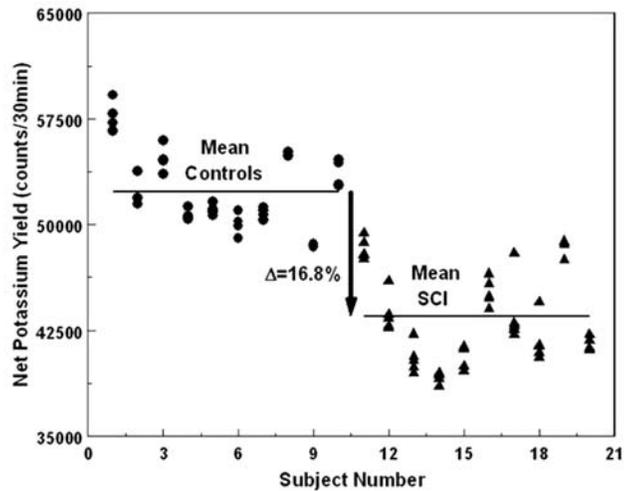


Figure 6. Comparison of the measurement of K in the legs of able-bodied control and SCI cohorts.

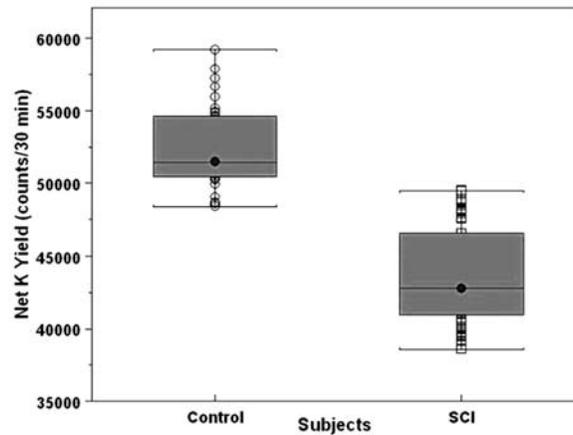


Figure 7. Box diagrams of net K counts, displaying clear separation between able-bodied control and SCI cohorts.

The points that appear in a column are the repetitive measurements of the same individual, which indicates good reproducibility of the system and for that of subject positioning; the horizontal lines connote the mean values for each of the groups, and the difference between these two groups is about 17%, with very small overlap.

The same data but is presented in a Box Plot Diagram (Figure 7) to permit further exploration of the distribution of the data; although the boxes are not identical, they are quite close, indicating similar distributions (similar skewness) without outliers, and the medians differ similarly to the average values.

In the Box Plot Diagram, there is a clear separation observed between the SCI and able-bodied control groups.

Of note, these preliminary results were not corrected for the volume of the legs (i.e., leg size) that may have influenced the absolute K value measured; methods in the future are being developed to calibrate and analyze the legs to account for differences in size.

## SUMMARY

In light of the fact that we are engulfed in a perpetual sea of natural radiation, it is difficult to put much credence on the notion that low levels of radiation, regardless how miniscule, will result in malignant transformation. The probability for cancer development per disintegration may be hypothesized to be very low because of the high number of disintegrations constantly ongoing in the body from natural isotopes, as well as the appreciation of the enzymatic repair of damaged DNA that serves to preclude the initiation of malignancy. The LNT hypothesis, which bears no scientific merit, fallaciously supports and satisfies the concerns of those who choose to err on the side of excessive caution. Additional problems with the LNT model arise with the definition of dose, or energy per unit mass (erg/g), at low levels of radiation exposure. When radioisotopes disintegrate (such as  $^{40}\text{K}$ ,  $^{14}\text{C}$ , and  $^3\text{H}$ , isotopes found in the body in sizeable amounts), they deposit a well known finite amount of energy ( $e_i$ ) in a very small volume. Thus, the concept of “dose” requires a degree of scientific rigor to attain meaningful internal consistency. The corpuscular nature of radiation interactions implies that  $e_i$  is deposited in a very small volume with mass ( $m_i$ ) of a micro-gram or less, which results in a high radiation dose,  $D_i=e_i/m_i$ , at the site of energy deposition. However, the same amount of energy averaged over a mass of one gram is quite low. Dose, being an intensive quantity, cannot be summed from different, distant locations as a measure of risk of radiation exposure. Thus, a threshold dose of localized exposure is required to cause sufficient damage to overwhelm the molecular repair apparatus.

On the other hand, it should be appreciated that single doses of radiation are not necessarily adverse to the organism if the “hits” are dispersed in the body over time, either failing to induce a “lethal” cellular event and/or failing to overwhelm the genomic repair apparatus. Thus, the probability for the conversion of a healthy cell to one that is pre-cancerous or cancerous per disintegration may be reasonably speculated to be extremely low because multiple, highly localized disintegrations in the vicinity of a single genome over a short time period may be required to induce malignancy.

The clinical utility and practicality of the measurement of naturally occurring endogenous  $^{40}\text{K}$  present in states of health and disease was discussed. The measurement of TBK, as

measured by WBC, in the historical development of models for the human body compartmental analysis, and its clinical significance for body composition analysis, was presented. Because 98% of K in the body is located in the intracellular compartment, and  $^{40}\text{K}$  is in equilibrium with total body K, its measurement provides a direct measure of total (i.e., by WBC) or regional (i.e., by PBK) cell mass, or lean tissue mass. PBK systems were presented that measured  $^{40}\text{K}$  in the brain, arm, and leg—that is, in regions of the body in which K is sufficiently high to be utilized for diagnostic purposes. The ability to obtain accurate and reproducible regional limb intracellular mass by direct  $^{40}\text{K}$  measurement will permit clinicians to better ascertain the effects of illness and/or inactivity on long-term residual muscle mass of the extremities by application of a direct and more precise methodology. This approach will then permit the evaluation of the efficacy, or lack thereof, of experimental interventions initiated to reduce muscle loss in various pathological conditions.

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