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Radiation Doses to Hanford Workers from Natural Potassium-40

DJ Strom
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February 2009

Pacific Northwest
NATIONAL LABORATORY

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Summary

The chemical element potassium is an essential mineral in people and is subject to homeostatic regulation. Natural potassium comprises three isotopes, ^{39}K, ^{40}K, and ^{41}K. Potassium-40 is radioactive, with a half life of 1.248 billion years. In most transitions, it emits a beta-minus particle with a maximum energy of 0.560 MeV, and sometimes a gamma photon of 1.461 MeV. Because it is ubiquitous, ^{40}K produces radiation dose to all human beings. This report contains the results of new measurements of ^{40}K in 248 adult females and 2,037 adult males performed at the Department of Energy Hanford Site in 2006 and 2007. Potassium concentrations diminish with age, are generally lower in women than in men, and decrease with body mass index (*BMI*). The average annual effective dose from ^{40}K in the body is 0.149 mSv y^{-1} for men and 0.123 mSv y^{-1} for women, respectively. Averaged over both men and women, the average effective dose per year is 0.136 mSv y^{-1}. Calculated effective doses range from 0.069 to 0.243 mSv y^{-1} for adult males, and from 0.067 to 0.203 mSv y^{-1} for adult females, a roughly three-fold variation for each gender. The need for dosimetric phantoms with a greater variety of *BMI* values should be investigated. From our data, it cannot be determined whether the potassium concentration in muscle in people with large *BMI* values differs from that in people with small *BMI* values. Similarly, it would be important to know the potassium concentration in other soft tissues, since much of the radiation dose is due to beta radiation, in which the source and target tissues are the same. These uncertainties should be evaluated to determine their consequences for dosimetry.

Acronyms and Abbreviations

Acronym	Meaning
ANSI	American National Standards Institute
BMI	body mass index
BOMAB	Bottle Manikin Absorption
DF	dose factor
DOE	U.S. Department of Energy
$\dot{E}$	effective dose rate
ICRU	International Commission on Radiation Units and Measurements
MBq	megabecquerel
MeV	megaelectronvolt
mGy	milligray
mSv	millisievert
NCRP	National Council on Radiation Protection and Measurements
PNNL	Pacific Northwest National Laboratory
RADAR	RAdiation Dose Assessment Resource
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

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1.0 Introduction

The chemical element potassium is an essential mineral in people and is subject to homeostatic regulation. Natural potassium comprises three isotopes, ^{39}K (93.2581 atom %), ^{40}K (0.0017 atom %), and ^{41}K (6.7302 atom %). Potassium-40 is radioactive, with a half life of 1.248×10^9 y. In 89.14% of transitions, it emits a β^- particle with a maximum energy of 0.560 MeV, and in 10.66% of transitions, it emits a gamma photon of 1.461 MeV.

Because it is ubiquitous, ^{40}K produces radiation dose to all human beings.

In this report, we present the results of new measurements of ^{40}K in Hanford workers, and analyze the dependence of potassium concentrations by age, sex, and body mass index. We report the results of past and present dose calculations, and make some recommendations for future research.

2.0 Materials and Methods

The five coaxial germanium detectors shown in Figure 1 are part of a scanning system that is used to estimate the activity of fission products, activation products, and ^{40}K in the body. The scanning system is located in a room with 30-cm thick steel walls to create an environment with low levels of ambient background radiation. The inside surfaces of the steel are covered with thin layers of lead, cadmium, and copper to filter the Compton scattered photons and characteristic x-rays generated from photon absorption in the steel. The system is configured for scanning measurements, and Figure 2 shows the counting arrangement with the detector cryostats and Dewars mounted on a carriage that moves the detectors under the counting platform. The individual lies in a supine position on a foam pad on the 1.9-cm thick plastic platform during the 10-minute measurement. The detectors move from the head to the hips during the first nine minutes. The last minute is spent moving from the hips down the legs at a faster scan speed.

Figure 1. Counting geometry for PNNL's coaxial germanium scanning system

Figure 2. Five coaxial germanium detectors and electronics

The system is calibrated using Bottle Manikin Absorption (BOMAB) Phantoms (ANSI 1999). The phantom shell walls are composed of high density polyethylene. A solid polyurethane tissue-substitute with radiation attenuation characteristics matching average soft tissue (ICRU 1989) is used to fill the volume of each of the 10 sections. The polyurethane makes up most of the mass of the phantom. The ^{40}K is uniformly distributed in the volume of polyurethane. The ^{40}K activity is not traceable to the National Institute of Standards and Technology. The potassium was added in the form of K_2CO_3. The estimated uncertainty in the ^{40}K activity in the phantom is ± 5%.

The relative standard deviation for the ^{40}K measurements is estimated as 10% based on 11 measurements performed on one adult male over a three-month period. Differences in activity distribution and size between an individual and the calibration phantom are additional sources of uncertainty and could result in an additional uncertainty of 10% to 20% in the measurement results. A longer counting time can be used to reduce the 4% to 5% uncertainty in the net count rate.

3.0 Results

Fractional potassium concentration values [K], expressed as mass of potassium divided by body mass (g K/kg body mass or parts per thousand by mass), were calculated based on in vivo ^{40}K measurements of 248 adult females and 2,037 adult males performed at the Department of Energy Hanford Site in 2006 and 2007. The potassium concentration in males is generally higher than the concentration in females due to a higher percentage of lean body mass in males. The average potassium concentration values decrease with age for both adult males and adult females as shown in Figure 3, as suggested by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1972) and quoted in (NCRP 1987). There are significant individual variations in potassium concentrations. The potassium concentration in males and females decreases with increasing values of body mass index (*BMI*) expressed as an individual's mass divided by the square of his or her height (in kg m^{-2}) as shown in Figure 4, again with significant individual variability about the population trend.

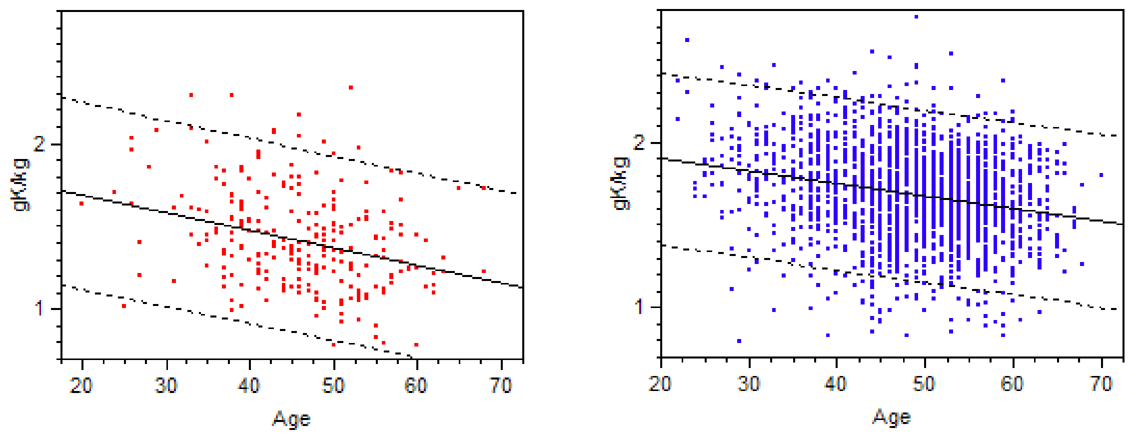

Figure 3. Potassium concentration [K] (grams of potassium per kg of body mass) decreases with increasing age in adult women (left panel) and men (right panel). Dashed lines show upper and lower 95% confidence intervals for the population.

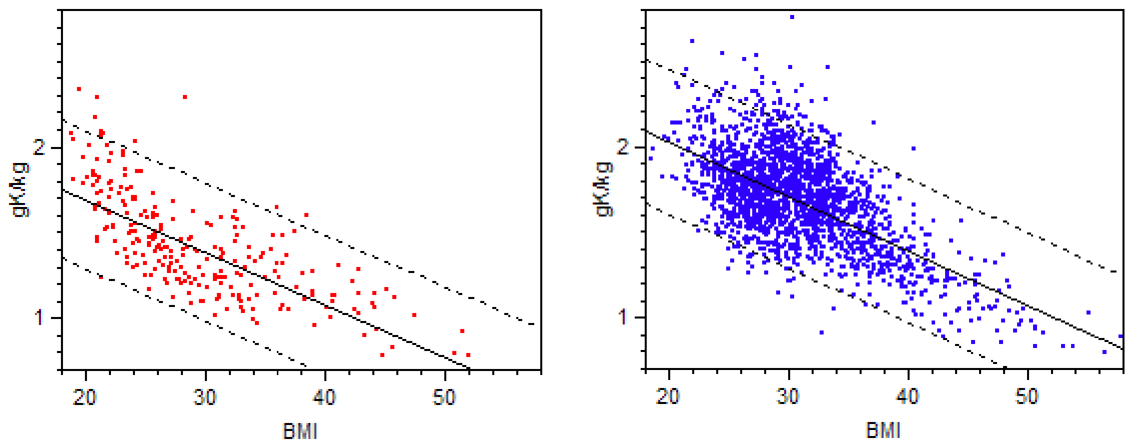

Figure 4. Potassium concentration [K] decreases with increasing body mass index (*BMI*) in adult women (left panel) and men (right panel). Dashed lines show upper and lower 95% confidence intervals for the populations.

Statistical properties of the data are given in Table 1 and Table 2. Data for males were more skewed to the right than a normal distribution, but less than a lognormal distribution. Data for females were lognormal.

Table 1. Summary statistics for adult potassium measurements [K] (expressed as grams of potassium per kilogram of body mass) by gender, age, and body mass index (*BMI*).

Gender	Number	Average ($g\ kg^{-1}$)	Std. Dev. ($g\ kg^{-1}$)	Geo. Mean ($g\ kg^{-1}$)	s_G [a]
Males	2037	1.682	0.273	1.66	1.187
Females	248	1.409	0.295	1.38	1.231

Gender	Parameter	Average	Std. Dev.	Minimum	Maximum
Males	Age (y)	48.8	8.58	22	70
Females	Age (y)	46.1	8.56	20	68
Males	BMI ($kg\ m^{-2}$)	30.9	5.32	18.5	57.8
Females	BMI ($kg\ m^{-2}$)	29.2	6.96	18.9	52.1

[a] s_G denotes geometric standard deviation.

Table 2. Single and double linear regression results of potassium content as a function of gender, age, and body mass index (*BMI*).

Gender	Intercept (g kg^{-1})	Slope: Age (g kg^{-1} y^{-1})	Slope: *BMI* (g kg^{-1} (kg m^{-2})$^{-1}$)	r^2	Geometric Standard Deviation s_G[a]
Males	2.664		-0.0318	0.384	
Females	2.306		-0.0307	0.524	
Males	2.047	-0.00747		0.055	
Females	1.897	-0.01058		0.094	
Males	2.946	-0.00620	-0.0311	0.421	1.133
Females	2.500	-0.00512	-0.0292	0.544	1.148

[a] The individual variation from the value predicted by these equations is lognormally-distributed about the *arithmetic* mean with this geometric standard deviation. The *geometric* mean of the lognormal distribution is equal to the arithmetic mean multiplied by $e^{-(\ln s_G)^2/2}$ (Strom and Stansbury 2000).

4.0 Dose Calculations

Dosimetry was performed from first principles as well as using the methods of Stabin and Siegel (2003). Standard phantoms were used from Cristy and Eckerman (1987) with the addition of the adult female phantom of Stabin and Siegel (2003).

Radioactive ^{40}K emits an 0.56 MeV average energy beta particle in 89.14% of transitions, and a 1.46 MeV photon in 10.66% of transitions (National Nuclear Data Center 2007). With a ^{40}K fractional abundance of 0.0117 atom % or 0.01196 mass % (NNDC 2007), natural potassium has a specific activity of 31.72 Bq g^{-1}. The possible energy per transition that can be absorbed ranges from 8.00×10^{-14} J if none of the 1.46 MeV photons are absorbed to 10.50×10^{-14} J if all of those photons are absorbed. In the 1987 Report, NCRP appears to have used an absorbed fraction of 0.8 (National Council on Radiation Protection and Measurements (NCRP) 1987).

Using "dose factors" (DFs; mGy MBq^{-1} s^{-1}) for ^{40}K in seven different phantoms from the RADAR web site (Stabin et al. 2008) and the Hanford age- and gender-dependent potassium data, yields the results in Table 3. The dose factors were for uniform whole body sources irradiating the whole body. On average, adult males have 19% more potassium per unit body mass compared to women, and receive 21% more absorbed dose. Of the 21% greater absorbed dose, 19% is due to the greater potassium concentration in men, while the remaining 2% is due to the increased absorption of the 1.46 MeV photon.

Table 3. Average dosimetric results using the dose factors (DF) from the RADAR site with Hanford potassium data for adult males and females. The adult female ^{40}K data were used for children.

Phantom		*DF* (mGy MBq^{-1} s^{-1})	Phantom Mass (g)	[K] (g $kg)^{-1}$	^{40}K activity per unit body mass (Bq kg^{-1})	^{40}K activity in the body (Bq)	Annual ^{40}K trans-itions (MBq s y^{-1})	Annual Abs. Dose (mGy y^{-1})
C&E[a]	Adult Male	1.20E-06	73,700	1.682	53.36	3,933	1.24E+05	0.149
S&S[b]	Adult Female	1.54E-06	56,800	1.409	44.70	2,539	8.01E+04	0.123
C&E[a]	15-yr-old	1.54E-06	56,800	1.409	44.70	2,539	8.01E+04	0.123
C&E[a]	10-yr-old	2.61E-06	33,200	1.409	44.70	1,484	4.68E+04	0.122
C&E[a]	5-yr-old	4.35E-06	19,800	1.409	44.70	885	2.79E+04	0.122
C&E[a]	1-yr-old	8.76E-06	9,720	1.409	44.70	435	1.37E+04	0.120
C&E[a]	Newborn	2.33E-05	3,600	1.409	44.70	161	5.08E+03	0.118

[a]C&E – Cristy and Eckerman (1987)
[b]S&S – Stabin and Siegel (2003).

None of the phantoms currently incorporate a variable body mass index. The adult male phantom has a BMI of 26.43, compared to the Hanford male average of 30.9. The absorbed fraction will be somewhat higher in bodies with higher BMI. The dose factor approach is consistent with a first-principles approach assuming an absorbed fraction of about 0.34 for the 1.46 MeV photon.

Figure 5 shows a modest increase in the effective dose with body mass, primarily due to increased absorption of the 1.46 MeV photon as mass increases.

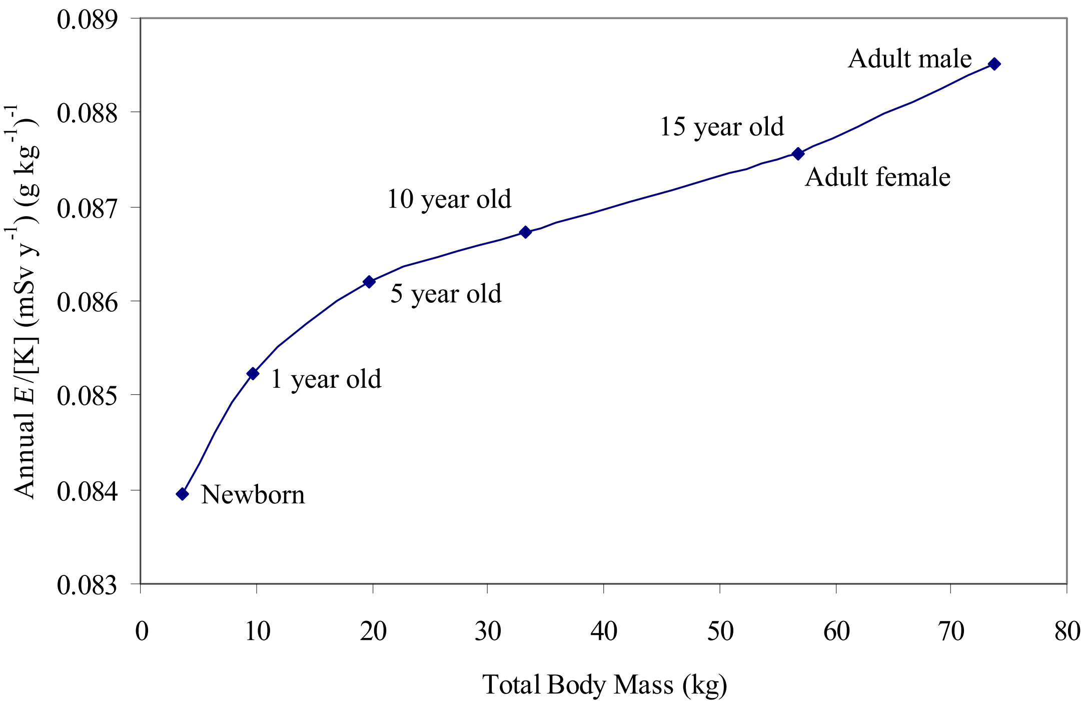

Figure 5. Effective dose per unit potassium concentration, E/[K], as a function of body mass for the phantoms in Table 3.

Trends in age dependence of average ^{40}K effective doses calculated using phantoms in Table 3 for males and females are shown in Figure 6 for the data from NCRP (1987) and for the Hanford data. Doses to adult males are about 8% lower at Hanford, probably due at least in part to the decreased ^{40}K concentrations associated with the higher average BMI of Hanford males. Doses to adult males are higher than those to adult females by an average of 32% in the NCRP data and 22% in the Hanford data.

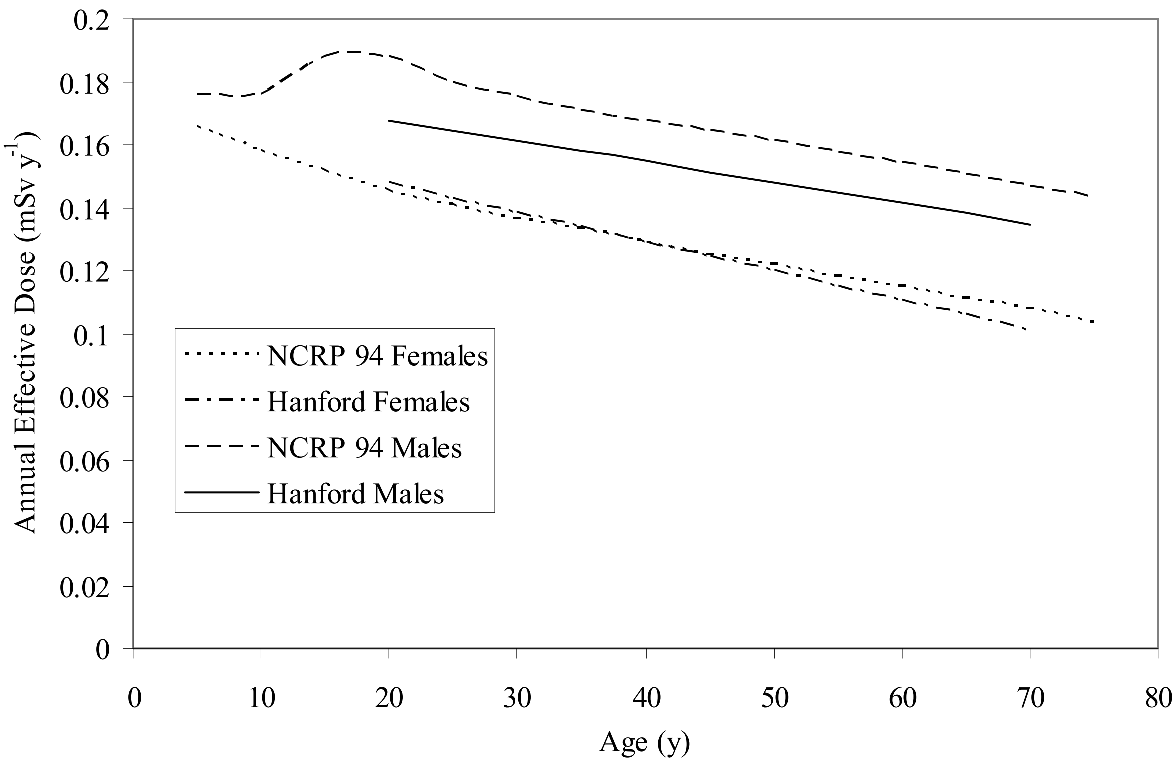

Figure 6. Trends in age dependence of average ^{40}K effective doses calculated using phantoms in Table 3 for males and females

5.0 Discussion

Significant data on potassium concentrations are unavailable for people under 20 years of age. Their lower body mass would result in a somewhat lower dose for a given potassium concentration, due to the greater escape probability of the 1.46 MeV photon. Data on potassium concentrations in young people are needed.

The decreasing mass fractions of potassium with BMI are not easily interpreted from the point of view of relevant dosimetry. Despite the data shown in Table 7.7 of NCRP Report No. 94 (1987), adequate data are not available on the distribution of potassium in organs and tissues of overweight or obese people. In particular, the Hanford data on an American worker population beg the question of whether lowered average potassium concentrations in persons with higher BMI indicate a lowered dose to tissues in which deposition of ionizing radiation energy causes detriment. Research focusing on dosimetry of alkali metals such as potassium and cesium as a function of BMI or other indicators is needed. The importance of dose to adipose or otherwise fatty tissues is not explicitly addressed in the literature. It is simply unknown what the importance of average alkali metal (e.g., ^{40}K or ^{137}Cs) dose is in persons with a BMI that differs significantly from the phantoms described by Cristy and Eckerman (1987) or Stabin and Siegel (2003).

In summary, the ubiquitous naturally-occurring radionuclide ^{40}K produces radiation doses that have significant trends with sex, age, body mass, and body mass index, with significant individual variability. The annual effective dose for average adult males as a function of age and BMI is

$$\dot{E}_{\text{Average Adult Male}} = \frac{0.0885\ \text{mSv y}^{-1}}{\text{g kg}^{-1}}\left(2.946 - 0.00620(\text{y}^{-1})\,Age(\text{y}) - 0.0311(\text{m}^2\ \text{kg}^{-1})\,BMI(\text{kg m}^{-2})\right)(\text{g kg}^{-1})$$

and for average adult females is

$$\dot{E}_{\text{Average Adult Female}} = \frac{0.0876\ \text{mSv y}^{-1}}{\text{g kg}^{-1}}\left(2.500 - 0.00512(\text{y}^{-1})\,Age(\text{y}) - 0.0292(\text{m}^2\ \text{kg}^{-1})\,BMI(\text{kg m}^{-2})\right)(\text{g kg}^{-1}).$$

Individual variability about these arithmetic mean values is described by a lognormal distribution with a geometric standard deviation s_G of 1.133 for males and 1.148 for females. The geometric means of these lognormal distributions are equal to the arithmetic means multiplied by $e^{-(\ln s_G)^2/2}$ (Strom and Stansbury 2000).

6.0 Conclusions

The average annual effective dose from ^{40}K in the body is 0.149 mSv y^{-1} for men and 0.123 mSv y^{-1} for women, respectively. Averaged over both men and women, the average effective dose per year is 0.136 mSv y^{-1}. Effective doses range from 0.069 to 0.243 mSv y^{-1} for adult males, and 0.067 to 0.203 mSv y^{-1} for adult females, a roughly three-fold variation for each gender.

Given the fact that there are many people with larger body mass index at Hanford than is used in current dosimetric phantoms, the need for dosimetric phantoms with a greater variety of *BMI* values should be investigated.

From our data, it cannot be determined whether the potassium concentration in muscle in people with large *BMI* values differs from that in people with small *BMI* values. Similarly, it would be important to know the potassium concentration in other soft tissues, since much of the radiation dose is due to beta radiation, in which the source and target tissues are the same. These uncertainties should be evaluated to determine their consequences for dosimetry.

7.0 References

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