Calibration and Measurement of Potassium-40 with a Whole-Body Counter

O. R. VAN REENEN, M. G. LÖTTER, P. C. MINNAAR, M. ITURRALDE

SUMMARY

Total potassium content in the human body may be obtained by measuring naturally occurring radioactive potassium-40, in a whole-body counter. The basic problem in calibrating the whole-body counter is discussed, as well as a phantom that is used to solve this problem. The normal potassium levels for men and for women were determined. Two additional parameters — lean body mass and total body water — derived from the potassium content, were also calculated.

S. Afr. Med. J., **48**, 2482 (1974).

Potassium, one of the electrolytes in the human body, participates in the propagation of nerve impulses, is a necessary biocatalyst and is involved in muscular contraction. About 98% of the body's potassium is stored intracellularly. The serum level, although extracellular, is a very important and critically controlled quantity. Normal levels range from 3,5 to 5 mmol/litre, whereas normal cells contain ± 140 mmol/litre.

The upper level in serum is controlled by excretion of potassium by the kidneys. The lower level is controlled by extraction of potassium from the body pool. There is sufficient evidence[1] that no correlation exists between serum levels and the total body content, basically because they are controlled by different mechanisms. The renal regulation of serum potassium is designed for the removal of excess potassium rather than for its conservation, whereas the body content is replenished by food intake only. The turnover of potassium is 2 - 3 g per day.

Two methods for measuring the total potassium content of the human body are available: (*i*) an isotope dilution technique using ^{42}K as a tracer for the exchangeable potassium pool; and (*ii*) counting of the naturally occurring radio-isotope ^{40}K.

Owing to its very long half-life of $1,3 \times 10^9$ years, ^{40}K is uniformly distributed throughout, comprises 0,0118% of all potassium and emits gamma rays with an energy of 1 460 keV. The average human body containing 100 g of potassium emits approximately 330 gamma rays per second. These gamma rays can be detected by means of the scintillation detectors in the whole-body counter.

One of the basic problems of this method is the calibration of the whole-body counter. Since the activity and exact distribution of the radioactive potassium in the body are unknown, some standard of known activity and geometry had to be used to convert the gamma counts to grams of potassium. Once the potassium content had been calculated, normal potassium levels could be determined.

Anderson and Langham[2] showed that potassium concentration, expressed in grams potassium per kg gross body mass, was a good index to normal levels. They found the potassium levels to be functions of both sex and age. Our first task was therefore to construct a phantom, or standard, for calibration purposes and also to obtain values by doing counts on normal individuals of both sexes and different age groups.

SUBJECTS AND METHODS

Equipment

A Nuclear Enterprise Whole-Body Counter Model NE 8102 equipped with two opposing scanning detectors was used. The detectors are NaI (Th) crystals of 10,2 × 12,7 cm, which are connected to a single-channel analyser system with window settings to count at the desired levels. The detection system is housed in a 15-cm thick steel-wall room of 2 × 2 × 2,5 m where the patient lies on a stretcher couch.

Description of Phantom

The phantom must have the following characteristics: (*i*) a simple geometrical shape approximating the body contour and dimensions as far as the major forms are concerned; (*ii*) enough flexibility to represent various body masses and lengths; (*iii*) the same isotope distribution as the human body.

The whole-body phantom proposed by Snyder *et al.*[3] (Fig. 1) consists of three principal sections: (*i*) an elliptical cylinder representing both head and neck; (*ii*) an elliptical cylinder representing the arms, torso, and hips; (*iii*) a truncated elliptical cone representing both legs and feet. The dimensions are representative of a man weighing 70 kg and 174 cm in height.

In order to comply with such a theoretical phantom, a method was devised to arrange one-litre saline plastic bags to simulate this geometrical configuration. These bags,

Departement of Biophysics, University of the Orange Free State and National Hospital, Bloemfontein
O. R. VAN REENEN
M. G. LÖTTER
P. C. MINNAAR

Department of Internal Medicine, University of the Orange Free State and National Hospital, Bloemfontein
M. ITURRALDE

Date received: 28 August 1974.

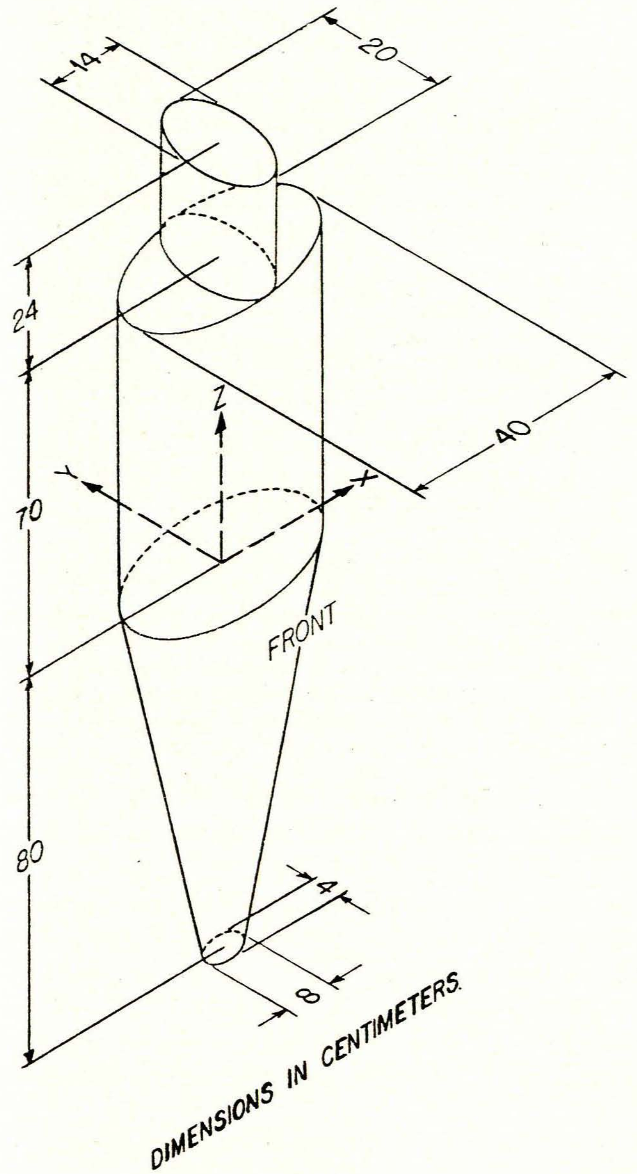

Fig. 1. Adult human phantom of 70 kg mass and 174 cm height (originally proposed by Snyder ***et al.***[3]**).**

measuring 20 × 10 × 5 cm, with a mass of 1 kg, are ideal for this purpose. The bags were all numbered. A computer programme was written whereby, given the mass and height of a patient, it calculated the exact distribution of the bags to simulate the patient's body according to a scaled version of the specified phantom. Table I is an example of the print-out. From a study of the potassium distribution in various parts of the body (Table II), it is clear that potassium is uniformly distributed throughout the body. By loading each saline bag with 2,14 g of potassium, the saline phantom geometrically simulated the human body as well as the potassium distribution. A 70-kg phantom therefore contains 150 g of potassium, equal to the content in an average male.

TABLE I. PHANTOM SCALED VERSION PRINT-OUT

Mass = 70 kg	Height = 174 cm
4 cm	**0,0 kg**
0 - 20 cm	**1 - 5 kg**
20 - 40 cm	**6 - 18 kg**
40 - 60 cm	**19 - 30 kg**
60 - 80 cm	**31 - 43 kg**
80 - 90 cm	**44 - 48 kg**
90 - 110 cm	**49 - 58 kg**
110 - 130 cm	**59 - 64,5 kg**
130 - 150 cm	**65 - 76,5 kg**
150 - 170 cm	**68 - 69 kg**
4 cm	**0,0 kg**

TABLE II. POTASSIUM CONTENT OF ADULT BODY ORGANS

Organ	Potassium (g/100 g)
Muscle	**0,36**
Skin	**0,11**
Brain	**0,33**
Liver	**0,22**
Intestine	**0,29**
Heart	**0,25**

When packed and placed on a couch these phantoms represented the various body shapes. The advantages of using this system for constructing a phantom are: (*i*) it is flexible—masses of 25 - 100 kg and heights of 150 - 195 cm can be simulated; (*ii*) it is easy to handle and construct; (*iii*) in addition to the potassium studies, a phantom may, for instance, have its liver replaced by a liver phantom loaded with ^{58}Co-vitamin B_{12}, permitting correct geometry, scattering and background values to be obtained; (*iv*) it is very cheap and easy to replace.

Counting Procedure

The patient, wearing a gown, is placed on the couch in the whole-body counter and scanned from the front and back for a total time of 2 160 seconds. Counts are recorded using the full photopeak of ^{40}K. On the same day, the background count and the counts from the patients' phantoms are determined.

Calculation of Potassium Content

The potassium content was calculated using the following formula:

$$\frac{(P-B)}{(F-B)} \times M \times 2{,}14 = \text{potassium content in grams}$$

where P = patient's count rate; B = background count rate; F = phantom count rate and M = mass of the patient (= mass of phantom).

RESULTS

As mentioned, Anderson and Langham[2] found a relationship between the potassium concentration, sex and age of an individual. Therefore, to obtain normal values, individuals of both sexes and different age groups were studied. The groups consisted of 45 trainee nurses, 18 years of age, and 37 male military trainees in the same age group.

The potassium concentrations obtained are listed in Table III. They were compared with normal values (Table IV), published by various authors using basically the same technique.

TABLE III. RESULTS OF POTASSIUM CONCENTRATION AND CONTENT

	Mean	SD*	Range
Men (18 years old)			
Body mass (kg)	71,4	11,4	52 - 105
Body height (cm)	176,9	8,5	160 - 193
Potassium content (mmol) ...	3 906,0	518,0	2 860 - 5 085
Potassium concentration (mmol/kg)	55,2	6,1	41,4 - 64,6
Women (18 years old)			
Body mass (kg)	61,4	8,7	47 - 86
Body height (cm)	164,0	6,7	150 - 181
Potassium content (mmol) ...	2 548,0	409,0	1 855 - 3 510
Potassium concentration (mmol/kg)	41,7	3,8	32,7 - 51,8

* Standard deviation.

TABLE IV. REPORTED POTASSIUM CONCENTRATIONS

Author	Number	Country	Pot. conc. (mmol/kg)
Men (18 years)			
McNeill and Green[8]	30	Canada	54,2
Anderson and Langham[2]	21	USA	55,0
Allen *et al.*[10] (using ^{42}K)	37	USA	54,2
Wayne *et al.*[11] (using ^{24}K)	7	Scotland	50,6
Women (25 - 49 years)			
MacGillivray *et al.*[9] (using ^{42}K)	32	Scotland	41,0
Allen *et al.*[10]	176	USA	41,7

Related Parameters

The relationship between the total body potassium content, lean body mass and total body water is already well established.[4,5] The lean body mass and total body water (Table V) were calculated as follows:

$$\text{Lean body mass} = \frac{\text{total body potassium content (mmol)}}{68,1}$$

and total body water = lean body mass × 0,732.

TABLE V. LEAN BODY MASS AND TOTAL BODY WATER DERIVED FROM POTASSIUM CONTENT

	Mean	SD	Range
Men (18 years old)			
Lean body mass (kg)	57,2	7,6	42 - 75
Total body water (kg)	41,8	5,6	30 - 55
% Body water (by mass)	59,2	6,6	44 - 70
Normal % body water:[7] men 17 - 34 years — 61,1% (range 53,3 - 70,3)			
Women (18 years old)			
Lean body mass (kg)	40,1	6,4	30 - 55
Total body water (kg)	29,3	4,7	21 - 40
% Body water (by mass)	48,0	4,5	38 - 60
Normal % body water:[7] women 20 - 31 years — 51,2% (range 46,5 - 59,9)			

DISCUSSION

Table III shows that a wide range of body shapes was included in the two groups. As can be seen in Fig. 2, there seems to be a linear correlation between potassium counts and body mass, or phantom mass. When the potassium concentration was calculated according to the above formula, no correlation was found between potassium concentration and body mass or body height (Fig. 3). Similar graphs were obtained for the 18-year-old women and the potassium concentrations compare very well with the normal values listed in Table IV. The conclusion is that the phantom used for the calibration compensated very well for the variations in body structure. Although calibration errors may still be present, in that the calculated values are not absolutely correct in terms of grams of potassium, such errors can only be shown by the use of ^{42}K.

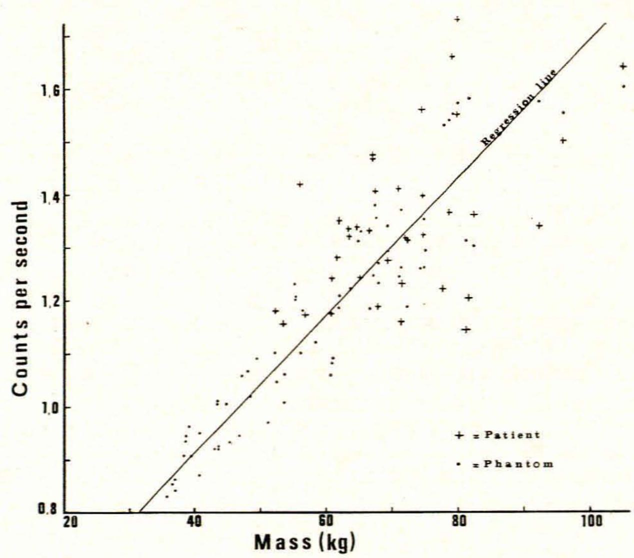

Fig. 2. The count rates of phantom (●) and patient (+) as function of body mass (phantom mass). The regression line was calculated on phantom data only: counts/sec = 0,0130 × phantom mass + 0,3915 correlation coefficient 0,882.

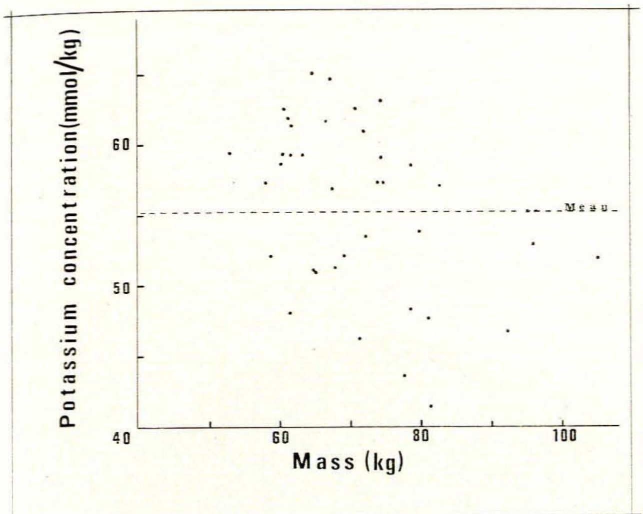

Fig. 3. Potassium concentration in mmol/kg as a function of body mass.

In Table III, the difference in the potassium concentration in the two sexes is very well demonstrated and correlates with the values obtained by Anderson and Langham.[2]

To confirm the validity of the total body potassium values, the lean body mass and total body water based on the total potassium content, were calculated. Forbes and Lewis,[6] by direct analysis of cadavers obtained a value of 68,1 mmol potassium per kilogram of lean body mass. Although this value may not be universally applicable, it was used to calculate the lean body mass. The total body water is stated to be 73,2% of the lean body mass.[7] The results are listed in Table V.

The normal values listed were obtained by using heavy water. The values listed in Table V, determined from the total potassium content of the individual, compare well with those of the heavy water method. The conclusion is that the estimate of the total potassium content is fairly accurate.

CONCLUSION

A mathematically calculated phantom was constructed to simulate various body shapes. Results indicate that the phantom correctly compensated for the various body shapes used in this study. It is difficult to estimate the exact limits for the phantom and great care should be taken in applying the phantom to masses below 40 kg and above 100 kg. Anderson and Langham[2] counting the potassium of 1 590 subjects with a 4π liquid scintillation counter, obtained good correlation between the potassium concentration and age of the individual but found a difference for the two sexes. Our results show a similar difference and compare well with the published values. The age-potassium concentration relation in the local population will also be determined as soon as sufficient data have been collected.

Future projects include determination of potassium concentrations in other age groups and normal values for the Black population.

We wish to thank Matron Lochner of the National Hospital, Bloemfontein, and Colonel Dippenaar, Medical Officer of the SA Defence Force, for their co-operation; and the South African Atomic Energy Board for financial support.

REFERENCES

1. Burke, S. R. (1972): *The Composition and Function of Body Fluids*, p. 43. St Louis: C. V. Mosby.
2. Anderson, E. C. and Langham, W. H. (1959): Science, **130**, 713.
3. Snyder, W. S., Fischer, H. L. jun., Ford, M. R. and Warner, G. G. (1969): J. Nucl. Med. (MIRD Publication suppl. 3, pamphlet 5).
4. Woodward, K. T., Trujillo, T. T., Schuch, R. L. and Anderson, E. C. (1956): Nature (Lond.), **178**, 97.
5. Belcher, E. H. and Vetter, H. (1971): *Radio-isotopes in Medical Diagnosis*, p. 285. London: Butterworths.
6. Forbes, G. B. and Lewis, A. M. (1956): J. Clin. Invest., **35**, 596.
7. Documenta Geigy (1962): *Scientific Tables*, 6th ed., p. 538 Basle: J. R. Geigy.
8. McNeill, K. G. and Green, R. M. (1959): Canad. J. Phys., **37**, 683.
9. MacGillivray, I., Buchanan, T. I. and Billewics, W. Z. (1960): Clin. Sci., **19**, 17.
10. Allen, T. H., Anderson, E. C. and Langham, W. H. (1960): J. Gerontol., **15**, 348.
11. Wayne, E. J., Bluhm, M. M. and Crooks, J. (1958): Studies of body composition in normal and pathological states using isotope dilution techniques. United Nations Second Conference on the Peaceful Uses of Atomic Energy. Geneva Papen A/Conf 15/P279. Vienna: **IAEA.**