Examination of Low-Sodium Salts for Radiation Education

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Various materials containing the natural radioisotope potassium-40 (40K) are often used for radiation education, but their radioactivity is not usually known. In the present study, low-sodium salts (LS salts) were purchased at several shopping malls in Japan, and the radioactivity of 40K in the LS salts were calculated from the nutritional tables and cutting down rates (CDR) printed on their packages. CDR is the percentage of sodium chloride (NaCl) in common salts replaced with potassium chloride (KCl). Solid disks were fabricated from the LS salts and KCl reagent, and their radiation count rates (cps/g) were measured by GM survey meter and CsI spectrometer. In these measurements, the KCl disk was used to determine the conversion factors (Bq/cps) for determining radioactivity of 40K in the LS salts. It was found that the experimentally obtained radioactivity generally coincides with that calculated from the nutritional tables, but it does not always coincide with that calculated from CDR.

Key Words: low-sodium salt, potassium-40, nutritional table, cutting down rate, radioactivity calculation, educational radiation source

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1. Introduction

All matter around us contains a certain amount of naturally occurring radioisotopes emitting radiation1–3). Typical examples are chemical fertilizers, kelp, and mushrooms. The substances composing such kinds of matter contain the natural radioisotope potassium-40 (40K)4,5) and are often used for radiation education, but their radioactivity is not usually known. To determine their radioactivity, accurate measurements using devices such as a germanium gamma-ray spectrometer are necessary; however, such measurements are not always possible, especially at junior and senior high schools. To resolve that inconvenience, low-sodium salts (LS salts)6–8), which are manufactured by replacing a part of the sodium chloride (NaCl) in commonly available salts (common salts) with potassium chloride (KCl), were investigated. Since these LS salts contain potassium (K), they also contain the radioisotope 40K, because natural K contains a small amount of 40K. The radioactivity of 40K can be calculated from nutritional tables and cutting down rate (CDR), namely, the percentage of NaCl replaced with KCl, which are printed on the packages of LS-salt products.

In the present study, seven brands of LS salts were purchased at several shopping malls in Japan, and radioactivity of 40K in them was calculated from their nutritional tables and CDR. Solid disks9) were then fabricated from the LS salts and KCl reagents (KCL). The dimensions of the disks were measured, and radiation intensity (cps) was determined by measurement using GM survey meter. Moreover, to identify radioisotopes in the LS salts, gamma-ray spectra of the solid disks were measured by CsI spectrometer. Radiation count rate
(cps/g) of the disks were also measured by GM survey meter and CsI spectrometer. In these measurements, the solid disk fabricated from KCL was used to determine a conversion factor (Bq/cps) for converting count rate to radioactivity. The conversion factor was applied to obtain radioactivity of the LS salts. In total, four radioactivity values were obtained: two values were calculated from the nutritional tables and CDR, and other two values were measured by GM survey meter and CsI spectrometer. The calculated radioactivities were then compared with the measured ones.

2. Examination and measurement methods

2.1 Salt and LS salts

Salt consists of odorless white crystals and is commonly used for preserving and flavoring food. For humans to maintain the correct volume of circulating blood and tissue fluids in the body\(^\text{10}\), the proper amount of salt is necessary. However, many people consume much more than the proper amount of salt. Such a high salt intake may result in harmful effects like hypertension, heart attacks, and kidney disease\(^\text{11}\). To prevent such over-consumption of salt, various brands of LS salts have been developed by food manufacturers.

The seven brands of LS salts examined in the present study were manufactured by replacing several dozen percentage of NaCl in common salt with KCl. That is, these LS salts are mixtures of NaCl and KCl. The K in KCl naturally contains three isotopes: \(^{39}\text{K}\), \(^{40}\text{K}\), and \(^{41}\text{K}\). Of these three, \(^{40}\text{K}\) is a radionuclide that emits 1312 keV beta radiation (89.3\%) and 1461 keV gamma radiation (10.7\%)\(^\text{4,5}\). Consequently, LS salts naturally emit these types of radiation and can be used as educational tools for teaching about radiation.

2.2 Calculation of radioactivity of \(^{40}\text{K}\)

Nutritional tables and CDRs are printed on the packages of the purchased LS salts. The nutritional tables give weight percentages of K. Radioactivity of \(^{40}\text{K}\) was calculated as follows (see Appendix I\(^\text{8}\)):

\[
A_{\text{Table}} = 0.311 \cdot C_{\text{K}(\%)}
\]  

where \(A_{\text{Table}}\) and \(C_{\text{K}(\%)}\) are radioactivity of \(^{40}\text{K}\) (Bq/g) calculated from the nutritional table and weight percentage of K (\%) in the LS salts. Radioactivity of \(^{40}\text{K}\) were also calculated from CDR as follows (see Appendix II):

\[
A_{\text{CDR}} = \frac{20.8 \cdot C_{\text{CDR}(\%)} \cdot (100 + 0.276 \cdot C_{\text{CDR}(\%)})}{(100 + 0.276 \cdot C_{\text{CDR}(\%)})}
\]  

where \(A_{\text{CDR}}\) is radioactivity (Bq/g) of \(^{40}\text{K}\) derived from CDR (\%) of the LS salt.

2.3 Measurement of \(^{40}\text{K}\) of solid disks

Solid disks were fabricated from LS salts, common salt, and KCL (YONEYAMA YAKUHIN KOGYO CO., LTD. Special Grade, Assay: 99.5\%). Radiation count was determined by 600-second measurement with the GM survey meter (Hitachi Ltd., TGS-146) and 3600-second measurement with the GM survey meter and CsI spectrometer (Monster II, Sanwa Corporation).

2.3.1 Fabrication of solid disks

A previously developed compression-and-formation method\(^\text{3,12–16}\) for compressing materials into solid disks by using a cylindrical stainless-steel mold (inner diameter: 35 mm; height: 30 mm) was applied to the seven brands of LS salt. About 20 g of LS salt was placed in the mold then compressed at compression pressure of around 150 kN for about three minutes. Ten solid disks, called “LS-salt sources,” were fabricated from the respective LS-salt brands. Another ten, called “KCL sources” and “common-salt disks,” were fabricated from KCL and common salt. The LS-salt sources and KCL sources were collectively called “disk sources”, which contain \(^{40}\text{K}\) and emit radiation. The disk sources and common-salt disks were collectively called “solid disks.” Consequently, a total of 90 solid disks were fabricated from nine types of raw materials, and their diameters, weights, and thicknesses were measured.

2.3.2 600-second measurement of LS-salt sources

To simply certify the existence of radioisotopes in the LS salts and KCL, radiation count rate (counts per second, cps) for each disk source was obtained by 600-second measurements using the GM survey meter. The measurement set up is shown in Fig. 1. The disk sources were put on the source stand, which was directly attached to the center of the head surface of the GM probe. This set up was used to measure 600-second radiation counts of ten disk sources fabricated from each raw material without common salt. The measurements were repeated three times for each raw material. Before, during, and after the three-repetition measurements, the disk sources were
removed once and background-radiation counts were measured five times by 600-second measurement. The obtained 600-second radiation counts of the ten disk sources and backgrounds were substituted into the following equation:

\[
C_{h,j} = \left( \frac{1}{600} \times \frac{3}{5} \sum_{k=1}^{5} c_{h,j,k} - \frac{1}{600} \times \frac{5}{2} \sum_{f=1}^{5} c_{h,bkg,f} \right)
\]

where \(C_{h,j}\) is net count rate (cps) obtained for disk source \(j\) (\(j: 1\) to \(10\)) fabricated from raw material \(h\) (\(h: 1\) to \(8\), numbers assigned to seven brands of LS-salt sources and KCL source); \(c_{h,j,k}\) is 600-second radiation count for disk source \(j\) fabricated from raw material \(h\) obtained from the \(k\)-th measurement (\(k: 1\) to \(3\), number of measurement repetitions), and \(c_{h,bkg,f}\) is 600-second background radiation count obtained from the \(f\)-th measurement without a disk source (\(f: 1\) to \(5\), number of background-radiation-measurement repetitions before, during, and after three-repetition measurements of the ten disk sources fabricated from raw material \(h\)). The above measurements determined net count rates of radiation (cps) for the 70 LS-salt sources fabricated from the seven brands of LS salts and for the ten KCL sources.

### 2.3.3 3600-second measurement of nine representative solid disks

The solid disks first fabricated from each of the seven brands of LS salts, KCL, and common salt were selected as representatives of the ten solid disks fabricated from the respective raw materials, and simply denoted as “LS-salt source\(_s\)”, “KCL source\(_t\)”, and “common-salt disk\(_n\)”. Seven different LS-salt source\(_s\) and the KCL source\(_t\) are collectively called “disk source\(_s\)”. The disk source\(_s\) and common-salt disk\(_n\) are collectively called “solid disk\(_s\)”. Therefore, there were nine solid disk\(_s\) first fabricated from the nine different raw materials, and 3600-second measurements with GM survey meter and CsI spectrometer were repeated ten times for nine solid disk\(_s\).

In the case of the GM survey meter, radiation counts of the 3600-second measurement could be directly read from the display of the survey meter. In the case of the CsI spectrometer, gamma-ray spectra were obtained first, and radiation counts of the 3600-second measurement were read from the area of the \(^{40}\text{K}\) peak region on the spectra. In both cases, average count rates (cps/g) and their standard deviations (cps/g) of ten measurements of the respective solid disk\(_s\) were determined.

In both the 3600-second measurements, the radioactivity of \(^{40}\text{K}\) contained in the KCL source\(_t\) was calculated under the assumption of weight abundance ratio of \(^{40}\text{K}\) in natural \(K\) (0.0120%\(^{8}\)), and resulting radioactivity was 16.2 Bq/g (Appendix I). Radiation count rates and calculated radioactivity of the KCL source\(_t\) were used to determine conversion factor for converting count rates (cps/g) to radioactivity (Bq/g)\(^{17,18}\). Common-salt disk\(_n\) was used to obtain background radiation count rates (cps/g). Experimentally obtained radioactivity was thus used to evaluate the radioactivity calculated by using Eqs. (1) and (2).

### 2.4 Data processing

#### 2.4.1 Conversion factors

In the measurements by both the GM survey meter and CsI spectrometer, the conversion factor was derived as follows (see Appendix III\(^{19,20}\)):

\[
F \pm \sigma_F = \frac{A_{KCL}}{G_{KCL} - G_{BKG}} \pm \frac{A_{KCL}}{(G_{KCL} - G_{BKG})^2} \left( \sigma_{GKCL}^2 + \sigma_{GBKG}^2 \right) \quad (4)
\]

- \(F\): conversion factor (Bq(cps),
- \(\sigma_F\): standard deviation of conversion factor \(F\) (Bq(cps),
- \(A_{KCL}\): calculated radioactivity of KCL source\(_t\) (Bq/g),
- \(G_{KCL}\): average gross count rate of KCL source\(_t\) measured ten times (cps/g),
- \(\sigma_{GKCL}\): standard deviation of \(G_{KCL}\) (cps/g),
- \(G_{BKG}\): average count rates of common-salt disk\(_n\) measured ten times (cps/g), and
- \(\sigma_{GBKG}\): standard deviation of \(G_{BKG}\) (cps/g).

Here, \(A_{KCL}\) is known to be 16.2 Bq/g, as stated in Section 2.3.3, \(G_{KCL}\) and \(\sigma_{GKCL}\) were experimentally obtained by ten 3600-second measurements of KCL source\(_t\), and \(G_{BKG}\) and \(\sigma_{GBKG}\) were experimentally obtained by the same measurement with common-salt disk\(_n\).
2.4.2. Radioactivity contained in LS-salt sources

The conversion factor determined as described above was used to determine radioactivity (Bq/g) contained in seven LS-salt sources as follows (see Appendix IV)\textsuperscript{19,20}:

\[
A_{LS} \pm \sigma_{LS} = F(G_{LS} - G_{BKG}) \pm F(G_{LS} - G_{BKG})
\times \sqrt{\left(\frac{\sigma_F}{F}\right)^2 + \left(\frac{\sigma_{GLS} + \sigma_{BKG}}{G_{LS} - G_{BKG}}\right)^2}
\]

\text{(5)}

\(A_{LS}\): radioactivity of \(^{40}\text{K}\) in the LS-salt source (Bq/g),
\(\sigma_{LS}\): standard deviation of \(A_{LS}\) (Bq/g),
\(F\) and \(\sigma_F\): as in Eq. (4),
\(G_{LS}\): average gross count rate of the LS-salt source, measured ten times (cps/g),
\(\sigma_{GLS}\): standard deviation of \(G_{LS}\) (cps/g), and
\(G_{BKG}\) and \(\sigma_{BKG}\) as in Eq. (4).

On the right side of Eq. (5), \(F\) and \(\sigma_F\) were obtained in the previous section by using Eq. (4), then \(G_{LS}\) and \(\sigma_{GLS}\) were experimentally obtained by ten 3600-second measurements of the LS-salt source.

3. Results and Discussion

3.1 Findings from nutritional tables

The numerical data extracted from the nutritional tables and CDRs printed on the packages are summarized in Table 1. Brand numbers “1 to 7” represent the seven brands of LS salts, and brand number “8” represents common salt. The abbreviated brand names are listed in the second column. CDR and weight percentages of Na, NaCl, and K contained in the LS salts and common salt are shown in the third to sixth columns. According to the food-labeling standards enacted by the food-labeling act in Japan, component contents in foods should be printed in weights contained per 100 g (or a package, …)\textsuperscript{21}. The weights contained per 100 g have the same numeric values as the weight percentages. In Table 1, the seven brands of LS salts are classified into two groups. The first group (1 to 4) contains LS salts with a CDR of 50% (50LS-salts), and the second group (5 to 7) contains those with CDR of 30% (30LS-salts). The vendors or manufacturers of the salts are listed in the last column.

3.2 Characteristics of 90 solid disks

Diameter, weight, and thickness of the 90 solid disks fabricated from the nine raw materials were measured. The results are listed in Table 2, where numbers “1 to 8” correspond to the brand and common-salt numbers listed in Table 1, and brand number “9” represents KCL. Average weight, thickness, and diameter and relative standard deviation (RSD) of ten solid disks fabricated from the respective raw materials are listed in the third to eighth columns. The bottom row represents the averages and their RSDs of nine averages of ten disks obtained for nine solid disks. It is concluded that because all their RSDs were less than 3%, the dimensions and weights of the 90 solid disks did not significantly vary due to individual fabrication and difference in raw materials.

In the last two columns, average and RSD of radiation count rate (cps) obtained by the 600-second measurements with the GM survey meter (ref, Section 2.3.2) are listed. These

| Brand number | Abbreviated brand name | Cutting down rate: CDR (%) | Weight percentage (%) | Vendor or manufacturer |
|--------------|------------------------|---------------------------|-----------------------|-----------------------|
| 1            | Yasasio                | 50                        | Na 18.1, NaCl —, K 27.6 | Ajinomoto Co., Inc.   |
| 2            | Naruto                 | 50                        | Na 19.5, NaCl —, K 25.9 | Tokyo Salt Co.        |
| 3            | Seto                   | 50                        | Na 18.8, NaCl —, K 26.8 | AEON Co., Ltd.        |
| 4            | Genen                  | 50                        | Na 18.2, NaCl —, K 27.4 | Nihonkaisui Co., Ltd. |
| 5            | Goto                   | 30                        | —, NaCl 68.6, K 12.5  | Ryouen Co.            |
| 6            | Herusio                | 30                        | Na 25.5, NaCl —, K 13.5 | Enyushoji Co.         |
| 7            | Kaien                  | 30                        | —, NaCl 68.8, K 12.4  | Ryouen Co.            |
| 8            | Salt*                  | —                         | Na 37.9, NaCl 96.3, K 0.154 | AEON Co., Ltd.       |

* Common salt
results show that difference between count rates for the ten LS salts fabricated from the same raw materials were very small because the RSDs are equal to or less than around 5%. These results prove that the nine solid disks selected in Section 2.3.3 can represent the ten solid disks fabricated from the respective raw materials.

3.3 Radionuclides contained in LS salts

To certify the existence of $^{40}$K in the LS salts, average gamma-ray spectra were constructed from ten spectra obtained by ten 3600-second measurements of the nine solid disks, as shown in Fig. 2. In the spectra, counts in each channel are averages of those of ten spectra. The position of a 1461 keV gamma-ray emitted from $^{40}$K was determined from the peak of the KCL source. The peak positions of the seven LS-salt source, coincident with that of the KCL source, and these peaks confirm the existence of $^{40}$K in the seven salt brands. However, the peak in the spectrum of common-salt disk is not clear. The spectra of the seven LS-salt source, were classified into two groups according to the difference in peak heights, the same as the cases of the CDRs. The pair of parallel vertical dotted lines show the range of peak areas from 1340 to 1580 keV. Count rates (cps/g) of spectra of the nine solid disks were derived from these peak areas. The obtained count rates are thus used below to determine conversion factors and radioactivity of $^{40}$K in the LS salts.

3.4 Radioactivity of radioisotope $^{40}$K contained in LS salts

Radioactivity of $^{40}$K was determined by four methods: two calculations, one from the nutritional tables (Eq. (1)) and one from CDR (Eq. (2)); and two measurements, one by GM survey meter and one by CsI spectrometer.

3.4.1 Calculated radioactivity of LS salts

Radioactivity calculated by using Eq. (1) is plotted as open circles in Fig. 3. The circles are bunched for four 50LS salts (1 to 4) and three 30LS salts (5 to 7), as two clusters. Radioactivity calculated by using Eq. (2) is shown as small black circles at every 10%, and the regression curve for those circles is also shown. Radioactivity of the 30 and 50LS salts derived by using Eqs. (2) are 5.76 and 9.14 Bq/g. All the open circles are under the regression curve, meaning that the radioactivity calculated by Eq. (2) is larger than that calculated by Eq. (1) by 7 to 14% and 38 to 50% for 50 and 30LS salts. That difference in radioactivities is further considered in Section 3.4.3.

| Brand number | Abbreviated brand name | Weight (g) | Thickness (mm) | Diameter (mm) | Radiation |
|--------------|------------------------|------------|----------------|---------------|-----------|
|              |                        | Average (g) | RSDa) (%) | Average (mm) | RSDa) (%) | Average (mm) | RSDa) (%) | Average (cps) | RSDa) (%) |
| 1            | Yasasio                | 20.42      | 0.45           | 10.84         | 1.11      | 35.17       | 0.03       | 3.37         | 1.64      |
| 2            | Naruto                 | 20.30      | 0.69           | 10.73         | 0.73      | 35.27       | 0.06       | 3.37         | 2.18      |
| 3            | Seto                   | 20.37      | 0.36           | 10.61         | 1.72      | 35.18       | 0.03       | 3.37         | 5.06      |
| 4            | Genen                  | 20.36      | 0.75           | 10.49         | 0.69      | 35.21       | 0.04       | 3.55         | 2.74      |
| 5            | Goto                   | 19.41      | 1.55           | 10.20         | 2.19      | 35.25       | 0.07       | 1.51         | 3.73      |
| 6            | Herusio                | 19.45      | 0.47           | 10.13         | 0.82      | 35.34       | 0.09       | 1.57         | 2.40      |
| 7            | Kaien                  | 19.39      | 0.70           | 9.97          | 1.34      | 35.24       | 0.05       | 1.54         | 3.35      |
| 8            | Saltb)                | 19.84      | 0.90           | 9.88          | 0.98      | 35.24       | 0.03       | —           | —         |
| 9            | KCL                    | 20.40      | 0.65           | 10.74         | 0.04      | 35.17       | 0.04       | 6.34         | 1.31      |
|              | Average and RSDa)      |            |                |               |           |             |            | 19.99       | 0.47      |
|              | of 9 solid disks       |            |                |               |           |             |            | 10.40       | 0.36      |

a) Relative standard deviation, b) Common salt
Fig. 2. Typical gamma-ray spectra of seven LS-salt sources, KCL source, and common-salt disk (background).

Fig. 3. Radioactivity calculated from the nutritional tables and cutting down rate (CDR) printed on the packages.
3.4.2 Measured radioactivity of LS-salt source1s

In the 3600-second measurements with the GM survey meter and the CsI spectrometer, count rates (cps) were obtained for the seven LS-salt source1s, KCl source1, and common-salt disk1. The count rates of the KCL source1 were used to derive the conversion factors by using Eq. (4). The resulting conversion factors were 54.05 ± 0.42 (Bq/cps) and 220.16 ± 2.61 (Bq/cps) for the GM survey meter and the CsI spectrometer. Values 0.42 and 2.61 are standard deviations (1σ) calculated from the second term on the right side of Eq. (4). The conversion factors were then used to determine radioactivity (Bq/g) of the respective LS-salt source1s by using Eq. (5).

Radioactivity and count rate obtained as described above are shown in Figs. 4(A) and (B). In the graphs, solid lines have inclinations of 54.05 and 220.16 in (A) and (B). These inclinations were determined from the conversion factors. The dotted lines represent upper and lower limits of the fluctuation range of 2σ from the solid lines. The radioactivity calculated from Eq. (5) is plotted as seven closed circles and one open circle with error bars (2σ) for the LS-salt source1s and KCL source1, where σ was calculated from the second term on the right side of Eq. (5). The confidence interval of 2σ was approximately 95%. About 95% of the determined conversion factors and radioactivities are within these fluctuation ranges.

The closed circles in Figs. 4(A) and (B) make two clusters representing four 50LS and three 30LS salts. The open circle of KCL is plotted alone and coincides with the radioactivity calculated using Eq. (1) within 4% (2σ). In the cluster of 50LS salts in (A), one closed circle (“3 Seto”) is somewhat lower than the other three. That may be because that impurities like bitterns (Mg, Ca, etc.) contained in the salt might affect the measurement of beta rays by the GM survey meter, although the details of this reduction in radioactivity could not be found. The radioactivities plotted in (A) and (B) coincide within the confidence interval of 2σ.

3.4.3 Evaluation of calculated radioactivity

Radioactivity calculated from Eqs. (1) and (2) were compared with those experimentally obtained by 3600-second measurements using the GM survey meter and the CsI spectrometer. The results of the comparison are summarized in Fig. 5. The closed circle and rhombus in black on the left side were calculated from Eq. (2) for CDRs of 50 and 30%. The other three open circles and three open rhombuses with error bars (2σ) show radioactivity averaged for four 50LS salts and three 30LS salts. These radioactivities were determined by using the nutritional table, GM survey meter, and CsI spectrometer. The four methods are represented by the notations “CDR,” “Table,” “GM,” and “CsI” along the horizontal axis in Fig. 5. The open square is radioactivity averaged for three 50LS salts without one 50LS salt (“3 Seto”). “Range 1” and “Range 2” mean the fluctuation region including 2σ of both results measured by the GM survey meter and CsI spectrometer.

In the case of CDR of 50%, all the average radioactivities determined by the four methods are within Range 1. However, in the case of CDR of 30%, the closed rhombus from CDR largely exceeds Range 2. This result means the calculation using CDR might overestimate radioactivity for the 30LS salts. This overestimation was about 45% (ref. in 3.4.1). On the contrary, radioactivity calculated from Eq. (1) (“Table” in Fig. 5) is almost within both Ranges 1 and 2. Radioactivities measured by the GM survey meter and CsI spectrometer coincide with those calculated from the nutritional tables within around 2σ, but they do not always coincide with those calculated from CDR. Consequently, CDR should be treated as a nominal value or guideline and the nutritional tables can be used for calculating radioactivity of 40K contained in LS salts.

4. Conclusion

Seven brands of low-sodium salts (LS salts) were examined in terms of their components (Na, NaCl, and K) and cutting down rates (CDR). CDR is the percentage of NaCl in common salt replaced with KCI. The seven brands of LS salts were classified into two groups: four LS salts with CDR of 50% (50LS salts), and three with CDR of 30% (30LS salts). Radioactivity of 40K contained in the LS salts was calculated from the nutritional tables and CDR printed on the packages. It was found that radioactivity calculated from CDR is larger than that calculated from the nutritional tables by around 9 and 45% for the 50LS salts and 30LS salts.

Ten solid disks were fabricated from each of nine types of raw materials (seven LS salts, KCI reagent, and common salt). The 90 solid disks thereby obtained had almost the same dimensions and weight regardless of individual fabrication and raw materials used. Moreover, radiation intensity (cps) of the LS salts fabricated from the same raw materials was roughly constant regardless of individual fabrication. Nine representatives of the ten solid disks fabricated from the nine different raw materials were selected, and their gamma ray spectra were measured. All the LS salts were found to contain the
Radioisotope $^{40}$K. Furthermore, radiation count rates (cps/g) were measured and conversion factor (Bq/cps) was determined, and radioactivity of the LS salts were derived by using the conversion factors.

Four values of radioactivity were obtained from two calculations and two measurements. The radioactivity calculated from the nutritional table coincides with that obtained by the measurements with both the GM survey meter and CsI spectrometer within around 2σ, but it does not always coincide with that calculated from CDR. Consequently, the nutritional table can provide original numerical data for calculating the radioactivity of $^{40}$K contained in LS salts, so
CDR should be treated as a nominal value or guideline. The results in the present study represent seven low-sodium salts. Although more low-sodium salts exist, the present results provide useful references for treating or considering the other ones.

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Appendix I

A1. Equation (1) to derive radioactivity from weight percentages of K

Radioactivity can be calculated by using the equations below:

\[ A_{\text{Table}} = \frac{dN}{dt} = \lambda N, \quad \lambda = \frac{0.6931}{T_{1/2}} \]

Then,

\[ A_{\text{Table}} = \frac{0.6931}{T_{1/2}} K_{ab} \frac{C(K\%) \times 6.022 \times 10^{23}}{100 \cdot M_{40K}} \]

\[ = \frac{0.6931}{4.027 \times 10^{-16}} \times 1.199 \times 10^{-4} \times C(K\%) \times 6.022 \times 10^{23} 
\times 40.00 \]

\[ = 0.3107 \times C(K\%) \quad (a) \]

\[ = 0.311 \times C(K\%) \quad (\text{Bq/g of LS-salt}) \quad (a1) \]

where \[ A_{\text{KCL}} \] is radioactivity of \(^{40}\text{K}\) in 1 g of KCl reagent.

A2. Radioactivity of \(^{40}\text{K}\) contained in KCl reagent used

Weight percentage of K in the KCl reagent \( C_{(K\%)} \) is given by

\[ C_{(K\%)} = \frac{[K]_m}{[KCl]_m} \cdot C_{\text{ass}(\%)} = 0.5245 \cdot C_{\text{ass}(\%)} \]

\([K]_m\): atomic weight of K (39.10),
\([KCl]_m\): molecular weight of KCl (74.55), and
\( C_{\text{ass}(\%)}\): assay of KCl reagent (%).

The assay is considered to be 99.50% according to the label on a reagent bottle of KCl used. It follows that

\[ C_{(K\%)} = 52.19\% \]

Substituting the above value into Eq. (a) gives

\[ A_{\text{KCL}} = 16.22 \text{ Bq/g} = 16.2 \text{ Bq/g} \]

Appendix II. Equation (2) to derive radioactivity from CDRs of LS-salts

Weight ratio \( R_{KCl} \) of KCl to LS-salt with \( CDR\% \) is given by

\[ R_{KCl} = \frac{CDR[KCl]_m}{CDR[KCl]_m + (100 - CDR)[NaCl]_m} \]

\([K]_m\) and \([KCl]_m\): as stated in Appendix I-A2, and
\([NaCl]_m\): molar weight of NaCl (58.44).

And weight ratio \( R_K \) of K to KCl is given by

\[ R_K = \frac{[K]_m}{[KCl]_m} \]

Weight percentage of K to LS-salt \( C_{(K\%)} \) is thus given by

\[ C_{(K\%)} = R_{KCl} R_K 100 \]

\[ = \frac{CDR[KCl]_m}{CDR[KCl]_m + (100 - CDR)[NaCl]_m} \cdot \frac{[K]_m}{[KCl]_m} \cdot 100 \]

\[ = 66.91 \text{ CDR} \]

\[ = \frac{100 + 0.2757 \text{ CDR}}{100} \]

Substituting \( C_{(K\%)} \) into Eq. (a) gives

\[ A_{CDR} = 0.3107 \times C_{(K\%)} = \frac{20.79 \text{ CDR}}{100 + 0.2757 \text{ CDR}} \]

\[ = \frac{20.8 \text{ CDR}}{100 + 0.276 \text{ CDR}} \quad (a2) \]

where \( A_{CDR} \) is radioactivity (Bq/g) of \(^{40}\text{K}\) derived from CDR (%) of the LS salts.

Appendix III. Equation (4) to derive conversion factor

Radioactivity of KCl reagent (KCl source1) is given \(^{19,20}\) by

\[ A_{KCl} \pm \sigma_{KCl} = (F \pm \sigma_F) \left( N_{KCl} \pm \sigma_{NKCl} \right) \]

\[ = N_{KCl} - \sigma_{\text{BGK}} \]

\[ \sigma_{NKCl} = \sqrt{\sigma_{\text{GKCl}}^2 + \sigma_{\text{BGK}}^2} \]

\[ A_{KCl}\]: as stated in the text (2.4.1),
\( \sigma_{KCl} \): standard deviation of \( A_{KCl} \) (Bq/g),
\( F \) and \( \sigma_F \): as stated in the text (2.4.1),
\( N_{KCl} \): net count rate of KCl source1 (cps/g),
\( \sigma_{NKCl} \): standard deviation of \( N_{KCl} \) (cps/g), and
\( G_{\text{BGK}}, \sigma_{\text{GKCl}}, \sigma_{\text{BGK}} \): as stated in the text (Section 2.4.1).
As $\sigma_{KCL} = 0$, because $A_{KCL}$ was calculated uniquely (A2). Then,

$$
\frac{A_{KCL}}{N_{KCL}} \pm \frac{A_{KCL}\sigma_{NKCL}}{N_{KCL}^2} = \frac{A_{KCL}}{G_{KCL} - G_{BKG}} \pm \frac{A_{KCL}\sqrt{(\sigma_{GKCL}^2 + \sigma_{BKG}^2)}}{(G_{KCL} - G_{BKG})^2}
$$

(a4)

where $A_{KCL} = 16.2 \text{ Bq/g}$, and $G_{KCL}$, $G_{BKG}$, $\sigma_{GKCL}$, and $\sigma_{BKG}$ are then obtained by measurement.

Appendix IV. Equation (5) to derive radioactivity of $^{40}$K

When conversion factor $(F \pm \sigma_F)$ is known, radioactivity of the LS salts source can be calculated as follows$^{19,20}$:

$$
A_{LS} \pm \sigma_{LS} = (F \pm \sigma_F) \left( N_{LS} \pm \sigma_{NLS} \right) = FN_{LS} \pm FN_{LS} \sqrt{\left( \frac{\sigma_F}{F} \right)^2 + \left( \frac{\sigma_{NLS}}{N_{LS}} \right)^2}
$$

$$
N_{LS} = G_{LS} - G_{BKG}
$$

$$
\sigma_{NLS} = \sqrt{\sigma_{GLS}^2 + \sigma_{BKG}^2}
$$

$N_{LS}$: net count rates of LS-salt source's (cps/g), $\sigma_{NLS}$: standard deviation of $N_{LS}$ (cps/g), and $A_{LS}$, $\sigma_{LS}$, $G_{LS}$, $G_{GLS}$, $G_{BKG}$, and $\sigma_{BKG}$ are as stated in the text (Section 2.4.2).

then

$$
A_{LS} \pm \sigma_{LS} = F(G_{LS} - G_{BKG}) \pm F(G_{LS} - G_{BKG}) \times \sqrt{\left( \frac{\sigma_F}{F} \right)^2 + \frac{\sigma_{GLS}^2 + \sigma_{BKG}^2}{(G_{LS} - G_{BKG})^2}}
$$

(a5)

where $F$ and $\sigma_F$ are determined in Appendix III, and $G_{LS}$, $G_{BKG}$, $\sigma_{GLS}$, and $\sigma_{BKG}$ can be obtained by measurement.