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REVIEW ARTICLE

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Estimation of concentration of radionuclides in skeletal muscle from blood, based on the data from abandoned animals in Fukushima

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Abstract

The damage caused by the earthquake on 11 March, 2011 resulted in a serious nuclear accident in Japan. Due to the damage to the Fukushima Daiichi Nuclear Power Plant (FNPP), large amounts of radioactive substances were released into the environment. In particular, one of the largest safety concerns is radioactive cesium (^{134}Cs and ^{137}Cs). Due to the FNPP nuclear accident, a 20 km area was restricted from human activity, and various types of domestic animals were left in the zone. We collected the organs and tissues from sacrificed animals to obtain scientific data to evaluate the internal deposition of radioactive compounds. At first, we found there is a strong correlation between blood ^{137}Cs and organ ^{137}Cs with data from 44 cattle, indicating that skeletal muscle is the target organ of deposition of radioactive cesium. Second, we analyzed the relationship between blood ^{137}Cs and muscle ^{137}Cs within relatively lower radioactive concentration, suggesting that estimation of concentration of ^{137}Cs is possible from blood concentration of ^{137}Cs. Finally, we developed computer software to estimate the muscle ^{137}Cs concentration from blood samples. Our study contributes to the food safety of livestock products.

KEYWORDS
cattle, radionuclides, skeletal muscle

1 | INTRODUCTION

The earthquake on 11 March, 2011 caused the nuclear accident of Fukushima Daiichi Nuclear Power Plant (FNPP), resulting in the release of huge amounts of radioactive substances into our environment (Bowyer et al., 2011; Kinoshita et al., 2011; Sinclair et al., 2011; Yasunari et al., 2011). Due to this accident, a 20 km area from FNPP was restricted for human activity. This evacuation zone contained large amounts of cattle, pigs, and chickens. The animals left in the evacuation zone are impossible to use for agricultural purposes, due to the deposition of the radioactive substances and safety regulations. However, the authors built the hypothesis that these animals might be useful models to evaluate the food safety of the radioactive substances. Furthermore, these animals might be the ideal materials to study the biological effects due to radioactive deposition by evaluating internal exposure.

1.1 | Distribution of radioactive substance within cattle in the FNPP evacuation zone

As a first step, a research group including the author revealed that the detailed distribution of radioactive substances with 44 cattle

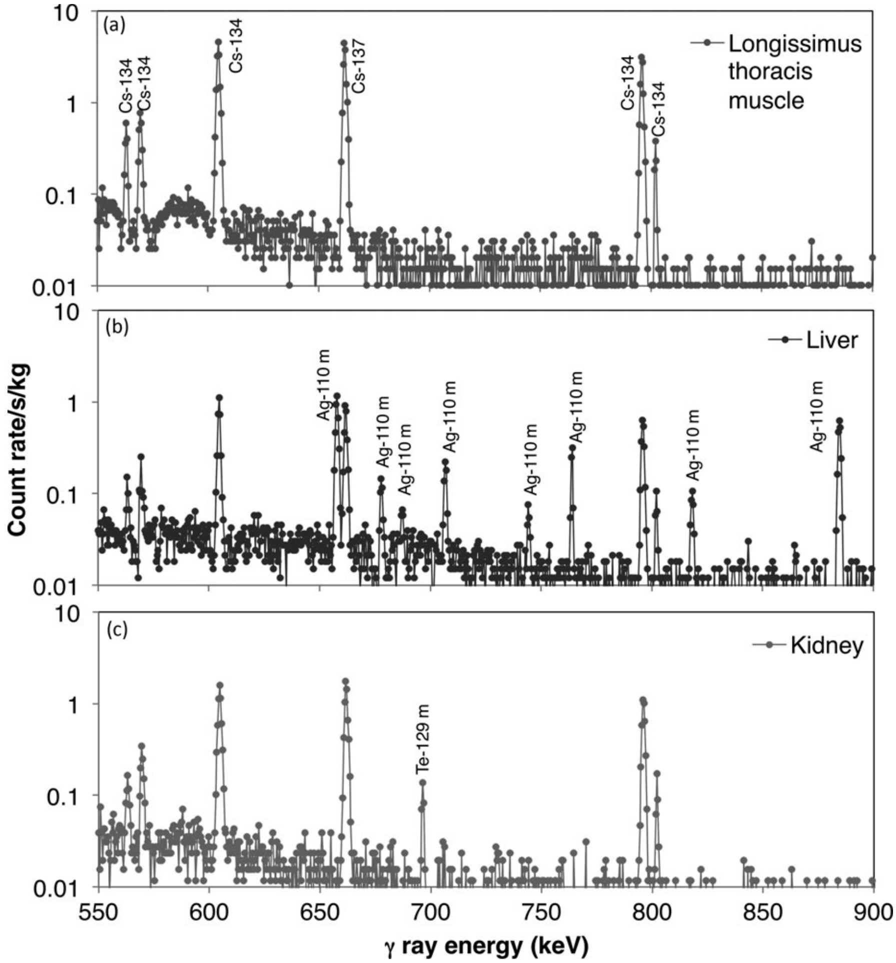

FIGURE 1 Representative detected photopeaks for internal radionuclides in organs of cattle. (a) Both peaks form ^{134}Cs and ^{137}Cs are highest in the muscle among organs measured. (b) Characteristic peaks to 110 mAg are observed in the liver but not in the muscle or the kidney. (c) A peak from 129mTe is observed in the kidney but not in the muscle or the liver. Copied from https://doi.org/10.1371/journal.pone.0054312.g001. No permission of copyright due to it being an open access document

(Fukuda et al., 2013). In all organs, radioactive cesium (^{134}Cs and ^{137}Cs) was detected including in fetus tissues. Furthermore, the deposition of ^{110m}Ag in the liver and deposition of ^{129m}Te in the kidney were detected (Figure 1). The concentration of ^{137}Cs in blood and concentration of ^{137}Cs in various types of organs are represented in Figure 2. The slope in Figure 1 shows the prevalence of radioactive ^{137}Cs deposition in various organs.

As shown in Figure 2, skeletal muscle showed the highest deposition of ^{137}Cs. Interestingly, although the biological significance is not clear, the heart muscle showed around half of the organ deposition, when compared with that of skeletal muscle. In 44 animals, the ^{137}Cs in skeletal muscle showed strong positive relationship with blood ^{137}Cs ($Y = 21.3X$, $R^2 = .83$). To be noted, the animals in Plot 1 and 3 are sampled in the same geographical location. While the animals in Plot 1 were fed contamination-free grass pasture, and were restricted within the barn, animals in Plot 3 had free access to the contaminated glass. Interestingly, the concentration of ^{137}Cs in the animals of Plot 1 was dramatically lower than that in Plot 3, indicating that the control of radioactive substance in feeding is quite important to control the internal exposure to radioactive substances.

1.2 | The relationship between blood ^{137}Cs and skeletal muscle ^{137}Cs in relatively lower doses

Within 1 year after the earthquake in 2011, the safety limitation of total radioactive cesium was set up to 500 Bq/kg. However, in April 2012, the safety regulation was lowered into 100 Bq/kg to ensure the safety of the foods in Japan. In Figure 3, 100 Bq/kg is close to the bottom of the graph, and it is not clear that positive correlation of ^{137}Cs still exists in relatively lower dose. From these situations, we analyzed the relationship between blood ^{137}Cs and skeletal muscle ^{137}Cs around the 500 Bq/kg area. We analyzed 17 materials to determine the possible relationship (Fukuda et al., 2015). In Figure 3, we showed the results of the analysis between blood ^{137}Cs and muscle ^{137}Cs. The results of the analysis showed that there is a positive correlation between blood ^{137}Cs and muscle ^{137}Cs around $Y = 27.1x$, and $R^2 = .742$.

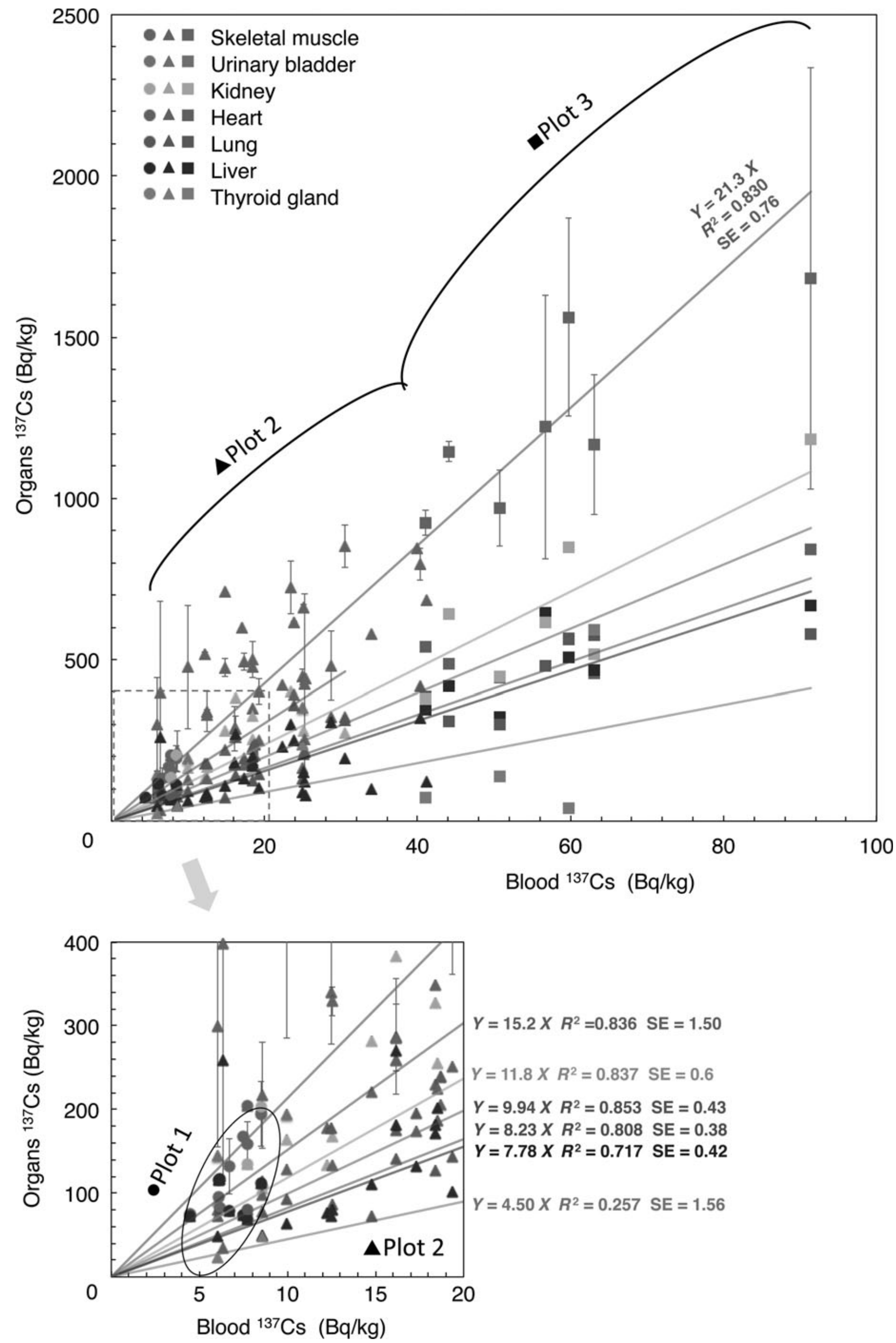

FIGURE 2 Correlation of ^{137}Cs activity concentration between peripheral blood (PB) and organs. Cattle were captured in Plots 1 (circle), 2 (triangle), and 3 (square). Cattle from the same plot were enclosed by black marking. Inset: cattle in which ^{137}Cs radiation concentration in PB was lower than 20 Bq/kg. All those from Plot 1 and part of Plot 2 were included. Copied from https://doi.org/10.1371/journal.pone.0054312.g001. No permission of copyright due to it being an open access document

1.3 | Computer software for estimation of the concentration of radioactive cesium in the skeletal muscle

To increase the accuracy of the estimation of muscle ^{137}Cs from blood ^{137}Cs, 88 samples were analyzed in total. As a result of the analysis, the estimation formula becomes $Y = 21.6x$, and $R^2 = .818$ (Fukuda et al., 2016). Based on these results, we developed personal computer-based software to estimate the radioactive concentration in the skeletal muscle from blood samples (Fukuda et al., 2016). The software was freely distributed, and was used for the estimation of total radioactive cesium in the fieldwork of livestock production (Figure 4). This software can contribute to ensuring food safety of livestock products.

1.4 | The safety evaluation studies with abundant animals, caused by the FNPP accident

Our research group showed that there is no functional abnormality in bull sperm cells, which were internally exposed to the radioactive substances of the FNPP accident (Yamashiro et al., 2014, 2015). Although our sperm data is negative, the data presentation of no abnormality would be an important milestone to study the

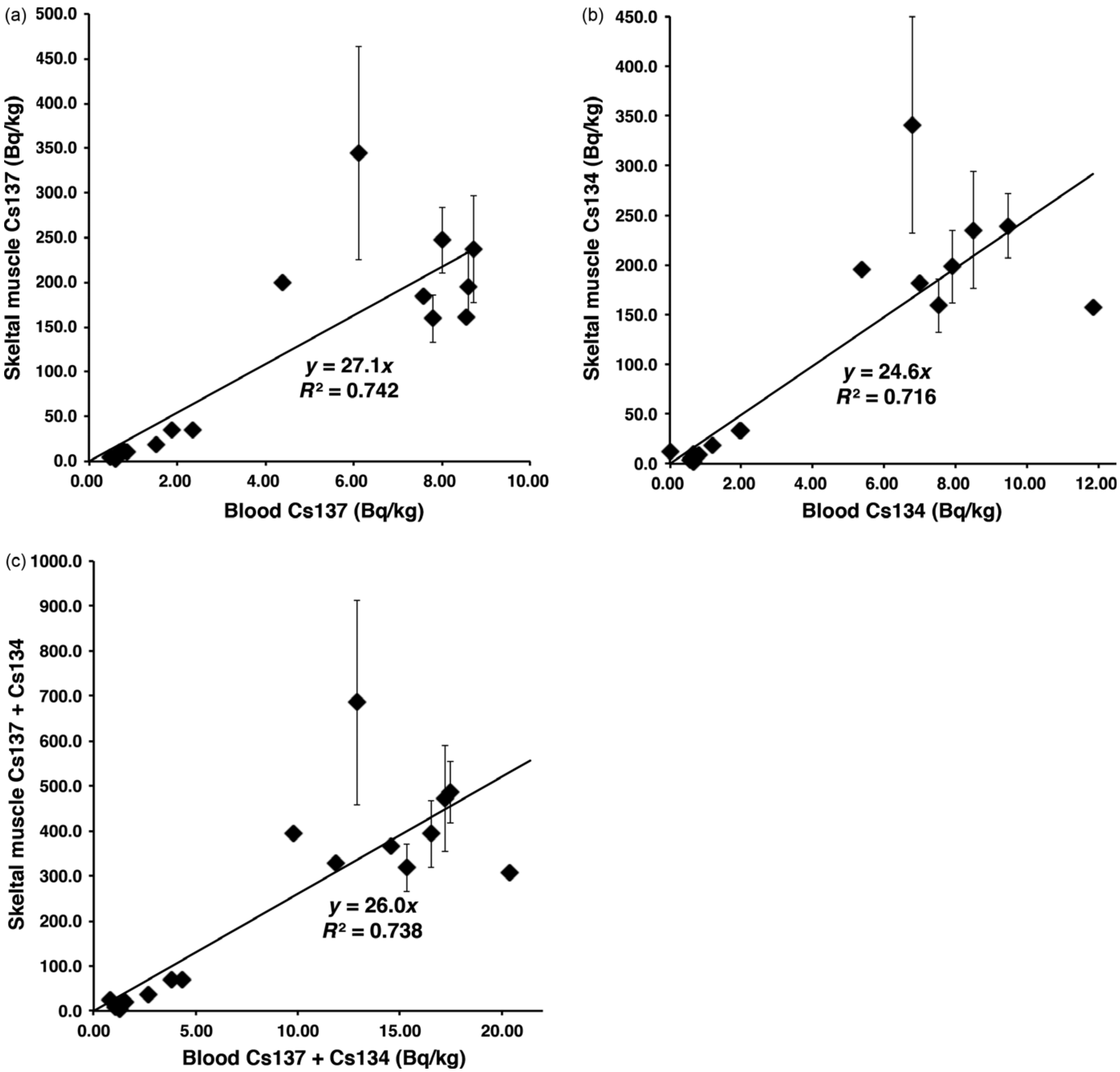

FIGURE 3 Cesium radioactivity in skeletal muscle and blood samples from cattle in the Fukushima Daiichi evacuation zone. A positive correlation was observed between blood and muscle radioactivity of ^{137}Cs (a), ^{134}Cs (b) and total radioactive cesium (^{137}Cs + ^{134}Cs) (c). Copied from https://doi.org/10.1111/asj.12301. Copyright permission number 4190701422677 from Wiley Blackwell

risk evaluation of human safety. Furthermore, we detected the existence of ^{90}Sr in teeth tissue of cattle, indicating the scientific evidence that ^{90}Sr was also released from the FNPP accident (Koarai et al., 2016). Our research group showed the existence of double-strand break DNA damage in lymphocyte cells derived from the abandoned cattle, which were detected by the immune-staining of gamma-H2AX foci (Nakamura et al., 2017). We also evaluated the radioactive compounds in ostrich (*Struthio camelus*) before and after the FNPP accident (Isogai et al., 2013). We also found out the plasma protein concentration and enzyme activities in cattle would be an indicator for external and internal exposure (Urushihara et al., 2016). Based on these scientific data, the risk assessment of radioactive compounds can be more accurately evaluated (Takahashi et al., 2015).

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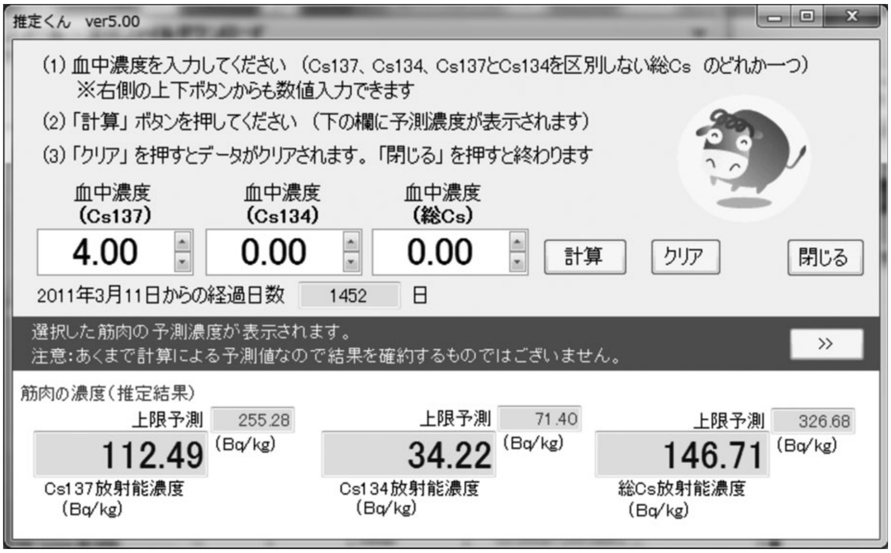

FIGURE 4 Software development to estimate the cesium radioactivity in skeletal muscle from blood samples. Appearance of the software for estimation. Copied from https://doi.org/10.1111/asj.12490. Copyright permission number 4190710114578 from Wiley Blackwell

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