DRINKING HIGH-ENERGY ELECTROLYTIC WATER DECREASES INTERNAL RADIATION EXPOSURE CAUSED BY THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT DISASTER

by

Masahiko SAWAJIRI* [1*]*, Shoichi MIYAMOTO* [2]*, Kohkoh YAMANOUCHI* [2]*, Shoji WADA* [3]*, Preeyaporn SRIMAWONG* [4**]*, Yuji NOMURA* [1]*, and Takashi UCHIDA [1]

[1] Institute of Biomedical & Health Sciences, Hiroshima University, Hiroshima, Japan
[2] Hijiri Environment and Development Co., Ltd., Koriyama, Japan
[3] Mikasa Shoji Co., Ltd., Osaka, Japan
[4] Faculty of Dentistry, Mahidol University, Bangkok, Thailand

Scientific paper
DOI: 10.2298/NTRP1602000S

The Fukushima Daiichi Nuclear Power Plant disaster on March 11, 2011, caused radiation hazards throughout Fukushima Prefecture. Cesium was absorbed by soil and plants and transferred to livestock. Removing radioactive cesium from the bodies of farm animals and humans is essential. It has recently been reported that H_2 scavenges reactive oxygen species and suppresses oxidative stress-related diseases. The hypothesis is that "active hydrogen" (hydrogen water) scavenges active oxygen species. We hypothesized that high-energy electrolytic hydrogen water will effectively decontaminate cesium-exposed chickens. A test group of chickens drank high-energy electrolytic hydrogen water, while the control group drank regular water. Cesium contents in the test group were significantly lower than in the controlled one, possibly because more cesium excretion occurred in the test group than the control group. Lower ^{137}Cs concentrations were found in test-group tissues than in control-group tissues, showing that high-energy electrolytic hydrogen water increased the rate of elimination of ^{137}Cs incorporated into chicken tissue.

Key words: cesium, internal exposure, decontamination, high-energy electrolytic

INTRODUCTION

In March 2011, Japan was hit by a massive earthquake (magnitude 9.0) and a subsequent tsunami. These events destroyed the reactors of the Fukushima Daiichi nuclear plant which underwent a partial meltdown. Large amounts of radioactive material were released into the atmosphere, seawater and soil, heavily polluting Fukushima Prefecture. Livestock within a 20 km radius of the plant were contaminated. Farmers were evacuated but were unable to take their domestic animals with them. However, they were allowed to keep the animals on the condition that the meat could not be sold to the public.

Contaminated meat from affected areas must be prevented from entering the food supply chain, and timely and appropriate management decisions must be made to protect human health. Effective management of the situation requires informed decisions to be made on when and how to decontaminate the animals. Some attention has been paid to decontaminating animal production facilities, vehicles and carcasses, but not enough notice to decontaminating live animals. Efficient methods for decontaminating large numbers of animals need to be developed and validated.

In July 2013, we measured radiation levels in the air over a sloping area in central Koriyama City, 60 km east of the Fukushima Daiichi nuclear plant. In the sampling area, the radiation dose ranged from 0.3 to1.3 μSv/h at 0.1 m above ground. Several high radiation sites ("hot points", where the radiation doses were 1.3 μSv/h), were found at the bottom of the slope, suggesting that radioactive material had been carried downhill by rainwater.

Cesium is absorbed by soil and, upon this, some of it absorbed by plants and transferred to livestock. The transfer of radioactive cesium through the food chain is of major concern. It is essential to find ways of removing cesium from the bodies of farm animals and humans.

The consumption of "hydrogen water" has been found to be followed by clinical improvements in sev-

* Corresponding author; e-mail: jiri@hiroshima"u.ac.jp
** This author contributed equally to this work

eral diseases. It has been hypothesized that active oxygen is effectively countered by "active hydrogen". Hydrogen water will scavenge active oxygen species and protect DNA from being damaged by oxygen radicals [1]. Electrolyzing water produces reduced species near the cathode and oxidized species near the anode. Hydrogen water contains a low dissolved oxygen concentration, a high dissolved hydrogen concentration, and a significantly negative redox potential.

Electrolytic hydrogen water contains many hydrogen molecules (H_2) that will scavenge reactive oxygen species and protect DNA from oxidative damage [2]. It has recently been reported that H_2 scavenges reactive oxygen species and suppresses various oxidative stress-related diseases [3]. However, the mechanism through which this occurs remains unclear. In the study described here, we attempted to remove radioactive cesium from chicken, hypothesizing that high-energy hydrogen water would effectively decontaminate the chickens.

In a recent study, it was found that H_2 suppressed radiation-induced acute injuries to lymphocytes and intestinal crypt cells [4]. However, the molecular mechanism through which the H_2-rich phosphate-buffered saline that was used in *in vitro* tests scavenged reactive oxygen species was not explored. In that study, a single intraperitoneal injection of H_2-rich saline was found to suppress late irradiation damage in mice *in vivo*, but it was also not clear how this occurred [4]. The detrimental effects of irradiation on biological tissues are largely related to the increased production of hydroxyl radicals (OH). H_2 was found to selectively decrease OH and peroxynitrite radical ($ONOO^-$) concentrations in *in vitro* tests and to have a therapeutic antioxidant activity in a rat model of middle cerebral artery occlusion [3]. In other studies, H_2 was found to offer protection from gamma radiation to cultured human cells and the mouse gastrointestinal tract [5, 6].

MATERIALS AND METHODS

With the consent of the landowners, soil samples from privately owned farmland in the northern part of Iwaki City and southern part of Fukushima City, Fukushima Prefecture, were collected. Collecting the soil samples from the farmlands did not affect any endangered or protected species. Radioactive cesium was extracted from the samples by mixing the samples with saline and incubating the mixtures at 95 °C for about 12 hours. Once the mixtures had cooled, the supernatants were sterilized by filtering. Each chicken used in the study was intraperitoneally injected with 20 mL of a 1.5 Bq/mL solution of the soil extracts. Each had a body weight of 2.5 kg. The radioactive cesium concentrations in the extract were measured using a gamma-ray spectrometer (LB2054; Berthold Technologies GmbH & Co. KG, Bad Wildbad, Germany).

The chickens used in the experiment were of the Aizu Jidori breed [7], only available in the Fukushima Prefecture. They were purchased from the Aizuregion area of the Fukushima Prefecture that was not contaminated with radioactivity. Aizu Jidori chickens can be bred and sold only by the Fukushima Prefecture Livestock Research Centre and the Aizu Jidori Net Company, the sole ones approved by the government of the Fukushima Prefecture to breed and sell the Aizu Jidori. The Ninjinsya Social Welfare Corporation owns a farm that is permitted by the Fukushima Prefecture Livestock Research Centre to breed Aizu Jidori. Chickens that were 100 days old were moved to Koriyama and bred there. The methods for their breeding and transportation were established by the government of the Fukushima Prefecture and observed. New rearing sheds designed to prevent dust and rain entering were constructed to ensure that radioactive contamination was excluded. The chickens were divided into two groups. One was given high-energy electrolytic hydrogen water to drink and the other group was given regular water. Chickens are classified as livestock, so ethical approval for performing the study was not required. However, we obtained the ethical approval from the appropriate institutions to sacrifice them. The experiment was carried out in accordance with the Guidelines of the Committee on Animal Experimentation of Hiroshima University and the Committee on Research Facilities for Laboratory Animal Science of the Natural Science Center for Basic Research and Development of Hiroshima University (permit number A13-110). Each chicken was decapitated to minimize suffering when sacrificed.

High-energy electrolytic hydrogen water was prepared by electrolysis at 200 V for 60 min, using three-phase AC electricity. The electrolysis was performed in an 80-L batch-type device equipped with stainless steel electrodes (GFX11-MA001; Hijiri Environment and Development Co., Fukushima, Japan). The high-energy hydrogen water that was prepared had a pH of 6.9 and a dissolved hydrogen concentration of 0.3 mg/L. It had a low redox potential (521 mV) and a low dissolved oxygen concentration (2.59 mg/L) in comparison to tap water (pH 7.0, dissolved hydrogen concentration 0.2 mg/L, redox potential 523 mV, dissolved oxygen concentration 7.69 mg/L). All of the values given are means. The measurements were performed at room temperature (TRUSTLEX ENH-1000, Sato Shouji INC., Osaka, Japan) and the measurement methods were approved by the Japanese Ministry of Health, Labour and Welfare.

The rearing shed had an area of about 35 m^2. It was divided in half, the test group occupying one and the control group the other half. Each chicken had free access to water and food. After the radioactive cesium had been injected, all excrement was collected each day.

The collected excrement was dried and the radioactivity of the dry excrement measured. Three chickens in each group were sacrificed in the first, third, and fifth week after injection. We analyzed the superficial pectoral, deep pectoral, and biceps femoris muscles, which are valued as food and called "sasami" (white meat), "muneniku" (breast meat), and "momoniku" (thigh meat), respectively, in Japanese. Each tissue sample was freeze-dried using a VD-16 freeze dryer (Taitec Corporation, Saitama, Japan) and homogenized. ^{137}Cs and ^{134}Cs in each sample were counted for 18 hours using the aforementioned gamma ray spectrometer. The results are expressed on a dry weight basis.

RESULTS

The chickens in both groups had similar weight gains, and the weight gains were similar to those found in chicken reared by Misato in Aizu. The dry weights of the tissue samples from the different groups did not differ significantly (fig. 1). Radioactive cesium concentrations in the excrement produced by the test group were high on the first day but much lower on the second one. However, the radioactive cesium concentrations in the excrement produced by the control group were 30% of the concentrations in the excrement produced by the test group on the first day and higher than the concentrations in the excrement produced by the test group on the second day (fig. 2). There were no significant differences between the radioactive cesium concentrations in the excrement produced by the test and control groups after the third day. Temporal changes in ^{137}Cs and ^{134}Cs concentrations, on a dry weight basis, in each tissue type were determined. The ^{134}Cs concentration in thigh meat reached a maximum 1 week after injection, whereas the concentrations reached maxima in the other tissues by the third week. The experiment was performed 4 years after the nuclear disaster, and ^{134}Cs, which has a shorter half-life than ^{137}Cs, was difficult to detect. The ^{134}Cs concentrations in samples from the two groups of chicken were not significantly different (fig. 3).

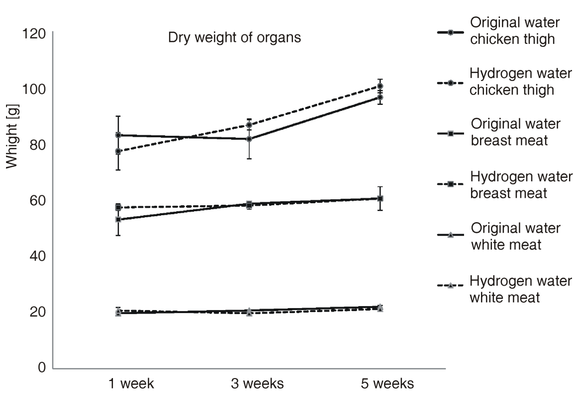

Figure 1. Dry weights of the tissue samples from the test group and control group chickens. The thighs gained weight throughout the 5 weeks of the experiment, but the other tissues gained little weight. No significant differences between the groups were found (*P < 0.05, N = 3 for each set of samples)

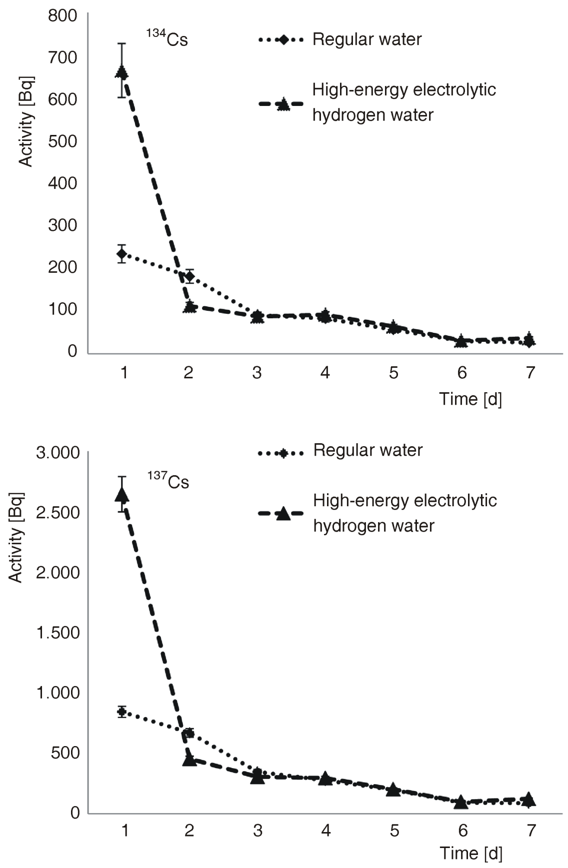

Figure 2. Radioactive cesium concentrations in excrement produced by the test group chickens (drinking high-energy electrolytic hydrogen water) and the control group chickens (drinking regular water). Large quantities of radioactive ^{134}Cs and ^{137}Cs were excreted by test group chickens on the first day after injection. The amounts of radioactive cesium excreted by control group chickens decreased slowly after injection. (*$P < 0.05$, $N = 3$ for each set of samples).

The ^{137}Cs concentrations were lower in the tissue samples from the test group than from the control group at almost all times after injection, most notably at 3 or 5 weeks after injection (fig. 4). However, the ^{137}Cs concentrations in the white meat of the control chickens increased between the first and third week and then decreased by the fifth week, reflecting the migration of radioactive cesium from the abdominal cavity to more peripheral tissues. In the fifth week, the ^{137}Cs concentrations in the white meat of the test group were less than 20% of the ^{137}Cs concentrations in the white meat of the control group. White meat is potassium rich, and potassium-cesium exchange occurs slowly in the white meat. The ^{137}Cs concentrations were lower in the test group tissues than in the control group tissues at the end of the study.

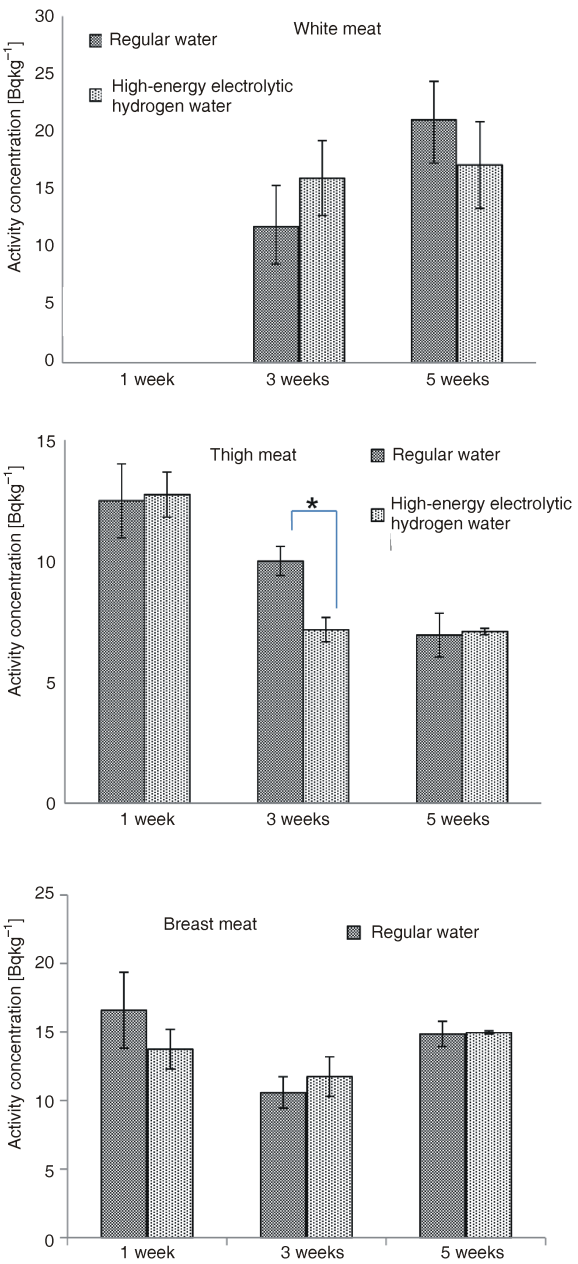

Figure 3. ^{134}**Cs concentrations (in Bq/kg dry weight) in different tissues at different times after a radioactive cesium extract was injected into test group chickens (drinking high-energy electrolytic hydrogen water) and control group chickens (drinking regular water). The concentrations in white meat increased over time. Concentrations in breast meat first decreased and then increased. Concentrations in thigh meat decreased over time. The temporal changes in the different tissues were significantly different (paired t-test, ****P*** **< 0.05,** ***N*** **= 3 for each set of samples)**

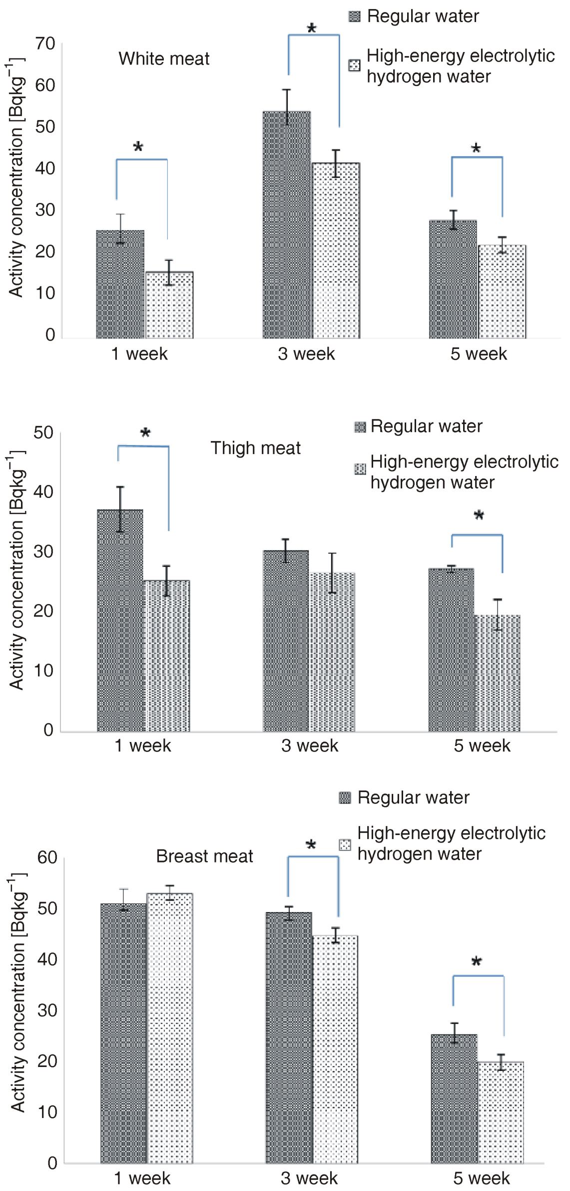

Figure 4. ^{137}**Cs concentrations (Bq/kg dry weight) in different tissues at different times after a radioactive cesium extract was injected into test group chickens (drinking high-energy electrolytic hydrogen water) and the control group chickens (drinking regular water). The concentrations were significantly lower in the test group than in the control group, particularly 5 weeks after injection. The concentrations in breast and thigh meat reached maxima 1 week after injection, but the concentrations in white meat reached maxima 3 weeks after injection (paired t-test, ****P*** **< 0.05)**

Overall, ^{137}Cs concentrations were ~40 % lower in the test group tissues than in the control group tissues 3 and 5 weeks after injection. We therefore concluded that drinking high-energy electrolytic hydrogen water caused radioactive ^{137}Cs to be efficiently removed from the bodies of the chickens.

DISCUSSION

Concentrations of ^{137}Cs in the breast and thigh meat samples were high in the first week after ^{137}Cs had been injected intraperitoneally (*i. e.*, cesium was taken up by these tissues relatively quickly). The ^{137}Cs concentrations in white meat samples, however, reached maxima 3 weeks after injection. White meat contains more potassium than do breast and thigh meat [8]. Cesium and potassium are both alkali metals. Potassium and ^{137}Cs exchange more slowly in potassium rich organs than in other organs.

Radioactive cesium was found in all of the tissues that were analyzed 3 and 5 weeks after injection. However, some of the cesium was excreted by the chickens, and this occurred more rapidly in the test-group than in the control-group. Concentrations of ^{137}Cs were significantly lower in test-group tissues than in the control-group tissues. Radioactive cesium concentrations in contaminated chicken decreased when high-energy hydrogen water was administered. We concluded that radioactive cesium is released by the body more quickly when hydrogen water is consumed than is the case with regular water.

It is costly to dispose of contaminated livestock that cannot be used to provide meat for human consumption, so decontaminating living livestock is important, whether or not the meat is subsequently marketable. Decontaminating livestock would decrease the cost of disposing of livestock that cannot be used to provide meat for human consumption.

It is very rare for radioactive cesium concentrations in food in Fukushima Prefecture to exceed the Japanese Ministry of Health, Labour and Welfare safety standards and for contaminated food to be discarded by producers. We monitored the elimination of radioactive cesium from chicken over time.

Internal exposure of livestock or humans to H_2 through consuming high-energy electrolytic hydrogen water is expected to promote the efficient excretion of radioactive cesium from the body. We used chicken breeding conditions from before the Fukushima disaster and assessed whether the consumption of electrolytic high-energy hydrogen water effectively decontaminated chickens injected with radioactive cesium.

The detrimental biological effects of ionizing radiation are principally caused by increased hydroxyl radical concentrations. Molecular H_2 has been found to selectively decrease the concentrations of cytotoxic reactive oxygen species such as OH and $ONOO^-$ in *in-vitro* tests [3]. H_2 has been found to have potential radioprotective effects [4] and to act as an antioxidant, decreasing the amount of DNA damage caused by radiation. H_2 effectively scavenges free radicals and attenuates radiation pneumonitis in mice (9, 10), but the precise mechanism involved has not yet been identified [6]. Such encouraging results prompted us to attempt to determine whether H_2 protects spermatogenesis and hematopoiesis from the effects of ionizing radiation.

We found that consuming high-energy electrolytic hydrogen water increased the rate at which tissue-incorporated ^{137}Cs was eliminated from chicken. Our novel approach may have wide applications. However, the exact mechanism involved in the decontamination process needs to be identified before high-energy electrolytic hydrogen water can be used after radiation accidents.

CONCLUSION

Cesium concentrations were significantly lower in test-group chickens than in control-group chickens, possibly because more cesium was excreted by the test-group than the control one. We used chicken breeding conditions from before the Fukushima disaster and our results suggest that consuming high-energy electrolytic hydrogen water effectively decontaminated chickens that had been injected with radioactive cesium. Drinking high-energy hydrogen water could decrease internal exposure to radioactive cesium. Humans and domestic animals will certainly experience internal exposure to radioactive cesium in the future because of soil pollution caused by the Fukushima Daiichi nuclear disaster, and high-energy hydrogen water could be used to decrease the amounts of internal exposure that occur. Internal exposure of livestock and humans to H_2 through consuming high-energy electrolytic hydrogen water is expected to promote the efficient excretion of radioactive cesium from the body.

AUTHORS' CONTRIBUTIONS

M. Sawajiri and S. Miyamotoput forward the idea for this study. S. Wada and K. Yamanouchi managed and fed the chickens. T. Uchida prepared the samples and Y. Nomura carried out the measurements. P. Srimawong processed the experimental data and performed the theoretical calculations.

REFERENCES

[1] Sakai, T., *et al*., Consumption of Water Containing over 3.5 mg of Dissolved Hydrogen Could Improve Vascular Endothelial Function, *Vasc Health Risk Manag., 10* (2014), pp. 591-597

[2] Shirahata, S., *et al*., Electrolyzed-Reduced Water Scavenges Active Oxygen Species and Protects DNA from Oxidative Damage, *Biophys Biochem Res Commun., 234* (1997), pp. 269-274

[3] Ohsawa, I., *et al*., Hydrogen Acts as a Therapeutic Antioxidant by Selectively Reducing Cytotoxic Oxygen Radicals, *Nat Med., 13* (2007), pp. 688-694

[4] Qian, L., *et al*., Radioprotective Effect of Hydrogen in Cultured Cells and Mice, *Free Radic Res., 44* (2010), pp. 275-282

[5] Qian, L., *et al*., Hydrogen-Rich PBS Protects Cultured Human Cells from Ionizing Radiation-Induced Cellular Damage, *Nucl Technol Radiat., 25* (2010), pp. 23-29

[6] Qian, L., *et al*., The Potential Cardioprotective Effects of Hydrogen in Irradiated Mice, *J. Radiat. Res., 51* (2010), pp. 741-747

[7] ***, Aizu Jidori net Co., Ltd., 2013, Available: http://www.aizujidori.net/jidori/. Japanese

[8] ***, Ministry of Education, Culture, Sports, Science, and Technology, Japan, Standard Tables of Food Composition in Japan, 2010, Available: http://www.mext.go.jp/component/b_menu/shingi/toushin/__icsFiles/afieldfile/2013/12/19/1299012_11.pdf. Japanese

[9] Zhao, L., *et al*., Hydrogen Protects Mice from Radiation Induced Thymic Lymphoma in BALB/c Mice, *Int. J. Biol. Sci., 7* (2011), pp. 297-300

[10] Terasaki, Y., *et al.*, Hydrogen Therapy Attenuates Irradiation-Induced Lung Damage by Reducing Oxidative Stress, *Am. J. Physiol. Lung Cell Mol Physiol., 301* (2011), pp. L415-L426

Received on December 16, 2015
Accepted on May 17, 2016