External dose estimates of laboratory rats and mice during exposure to dispersed neutron-activated $^{56}$Mn powder

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(Received 2 November 2021; revised 13 April 2022; editorial decision 22 May 2022)

ABSTRACT

Estimates of external absorbed dose in experimental animals exposed to sprayed neutron-activated $^{56}$Mn powder are necessary for comparison with internal absorbed doses estimated under the same exposure conditions, which is required for a correct interpretation of the observed biological effects. It has been established that the measured dose of external absorbed dose as a result of gamma irradiation range 1–15 mGy, which is order of magnitude less than the maximal dose of internal gamma and beta irradiation of the whole body of the same experimental animals irradiated under the same conditions; according to the available literature data, the maximal values of absorbed dose of internal gamma-beta irradiation of the whole body are in the range of 330 mGy–1200 mGy for mice and 100 mGy–150 mGy for rats. It is concluded that under the conditions of experiments with dispersed neutron-activated powder $^{56}$MnO$_2$, internal gamma-beta irradiation of experimental animals is the main factor of radiation exposure compared to external gamma irradiation.

Keywords: sprayed neutron-activated $^{56}$Mn powder; laboratory animals; dosimetry of external gamma-irradiation; radiophotoluminescence glass dosimeters
INTRODUCTION
Special radiation biological experiments were carried out using neutron-activated radioactive $^{56}$MnO$_2$ powder sprayed over laboratory rats and mice [1–4]. These radiobiological experiments were undertaken in order to estimate the peculiarities of biological effects in experimental animals exposed to sprayed neutron-induced $^{56}$Mn radioactive microparticles, which is related to the interpretation of the effect of radioactive particles fallout from the atomic bomb. The radionuclide $^{56}$Mn (T$_{1/2}$ = 2.58 h) is one of the dominant neutron activated emitter during the first hours following the neutron irradiation as a result of A-bombing [2]. Estimates of external absorbed doses in experimental animals are necessary for comparison with internal absorbed doses evaluated under the same exposure conditions, which is required for a correct interpretation of the observed biological effects [5–11].

MATERIALS AND METHODS
Conditions of irradiation
All works with experimental animals were approved by the Ethics Committee of Semey State Medical University, Kazakhstan, according to directive 2010/63/EU of the European Parliament and the Council of the Office on protection of animals used for scientific purposes of 22 September 2010 (Directive 2010/63/EU 2010) [12].

Experiments were carried out at the IVG.1 M research reactor located in the Republic of Kazakhstan [13]. Details of irradiation procedures were described in [4, 5, 14–16]. Shortly, these procedures were as follows. Thermal neutrons of the reactor (fluence of $4 \times 10^{14}$ n/cm$^2$) were used for neutron activation of the MnO$_2$ powder (100 mg of powder). Initial activities of sprayed neutron-activated $^{56}$MnO$_2$ powder were equal to $0.8 \times 10^8$ Bq, $2.74 \times 10^8$ Bq, $5.5 \times 10^8$ Bq and $8 \times 10^8$ Bq in different experiments. Special cages with experimental animals were installed inside sealed boxes [4] (see Fig. 1).

The dispersion of $^{56}$MnO$_2$ powder in the cages with experimental animals was conducted using special pneumatic system (see Fig. 2).

To exclude the possibility of $^{56}$Mn powder particles getting into the working room, the cage (2) with biological objects is placed in an isolated external chemical box (1). A pneumatic hose (3) is connected to the cage (2) for supplying the sprayed radioactive powder from the shielded cylindrical container with $^{56}$MnO$_2$ powder (5) forced by an impulse of compressed air flow via tube (4). The cage with animals (2) has a double bottom, into which an air stream is fed through a special hose (6). An inflow of fresh air is provided through special holes-perforations of the cage (2), which is necessary to maintain the vital functions of experimental animals during the experiment. In the upper part of the cage (2), the Petryanov’s filter is placed, which retains the radioactive powder’s dust particles when spraying.

One or two of these cages were used in different experiments. From six to nine experimental animals (mice or rats) were placed inside of each cage depending on the purpose of the corresponding biological experiments.

Characteristics of radiation source
The energies with abundance from beta- and gamma-rays due to beta-decay of $^{56}$Mn are presented in Table 1.

According to Table 1 the most intensive gamma-lines are: 0.8468 MeV (0.9890 quanta per decay), 1.8110 MeV (0.2720 quanta per decay); 2.1130 (0.1430 quanta per decay).

Measurements
Radiophotoluminescence glass dosimeters (Model GD-302 M, AGC Techno Glass Co., Ltd.) were used for external absorbed dose measurements. The reader FGD-1000 (AGC Techno Glass Co., LTD) was used to measure the intensity of the luminescence signal, which is proportional to the absorbed dose. Before exposure of the radiophotoluminescence glass dosimeters an annealing process was performed at 400˚C for 1 h using an electric furnace to remove residual luminescence signal from possible previous irradiation. Before reading the luminescence signal from the irradiated fluorescent glass dosimeters, they were preheated at 70˚C for 30 min to stabilize the fluorescent components.
Table 1. Energies with abundance from beta- and gamma-rays due to beta-decay of\(^{56}\text{Mn}\) (\(T_{1/2} = 2.58\) h) [17]

| Emission type | Mean energy, MeV | Frequency, quanta or particles per decay |
|---------------|------------------|-----------------------------------------|
| beta-1        | 0.0736           | 0.0002                                  |
| beta-2        | 0.0992           | 0.0116                                  |
| beta-3        | 0.1905           | 0.0004                                  |
| beta-4        | 0.2553           | 0.1460                                  |
| beta-5        | 0.3820           | 0.2790                                  |
| beta-6        | 0.6364           | 0.0006                                  |
| beta-7        | 1.2170           | 0.5630                                  |
| gamma-1       | 0.8468           | 0.9890                                  |
| gamma-2       | 1.0380           | 0.0004                                  |
| gamma-3       | 1.2380           | 0.0010                                  |
| gamma-4       | 1.8110           | 0.2720                                  |
| gamma-5       | 2.1130           | 0.1430                                  |
| gamma-6       | 2.5230           | 0.0099                                  |
| gamma-7       | 2.5980           | 0.0002                                  |
| gamma-8       | 2.6570           | 0.0065                                  |
| gamma-9       | 2.9600           | 0.0031                                  |
| gamma-10      | 3.3700           | 0.0017                                  |

The day after the preheating treatment, glass dosimeters were read by the reading device FGD-1000. Ultraviolet light (wavelength 355 nm) was applied for excitation of luminescence (range of wavelength from 600 nm to 700 nm), which is proportional to the absorbed dose.

The results of the absorbed dose measurements of glass dosimeters obtained from the fluorescence readings by the reading device FGD-1000 were multiplied by the air kerma calibration factor and by the coefficient of conversion to tissue kerma. The air kerma calibration factor was determined by irradiation in the \(^{60}\text{Co}\) standard irradiation field of the National Institute for Quantum and Radiological Science and Technology (Japan).

Results of external dose measurements are presented in Tables 2 and 3.

It should be noted that the number of exposed experimental animals in different exposure sessions was different (see Tables 2 and 3)—in dependence on the purpose of the corresponding biological experiments.

According to Table 2, number of mice in each cage is equal to nine in a case when two cages were placed inside the same isolated external box during exposure. There were two cages located next each other in the same isolated external box during the same exposure in that case. As a result 18 mice were irradiated in that case. Number of exposed mice was equal to six in the cage when one cage only was placed inside the isolated external box during exposure. As a result six mice were irradiated in that case (Table 2).

According to Table 3, number of rats in each cage was different during different exposure sessions: nine rats or six rats. As a result 18 rats or 12 rats, respectively, were irradiated during different exposure sessions. Two cages were located next each other inside the same isolated external box during all exposure sessions.

As seen in Tables 2 and 3, the doses of external irradiation depend not only on the amount of activity of the sprayed radioactive powder, but on the number of animals in the same cage during different exposure sessions, as well as on the number of cells nearby during exposure.

For better clarification of these circumstances Figs 3 and 4 show in comparative view the dependences of the measured doses of external radiation on the number of the animals in the same cage during different exposure sessions.

Table 2. Results of external dose estimates among experimental mice during exposure to dispersed neutron-activated \(^{56}\text{MnO}_2\) powder. The background absorbed dose has been subtracted

| Initial activity of sprayed \(^{56}\text{MnO}_2\) powder, Bq | Tissue kerma, mGy | SD, mGy | Number of mice in each cage during exposure | Number of cages in the same external box during exposure |
|-------------------------------------------------------------|-------------------|--------|------------------------------------------|--------------------------------------------------------|
| \(0.80 \times 10^8\)                                       | 0.81              | 0.21   | 9                                        | 2                                                      |
| \(2.74 \times 10^8\)                                       | 1.43              | 0.28   | 6                                        | 1                                                      |
| \(2.74 \times 10^8\)                                       | 1.98              | 0.19   | 9                                        | 2                                                      |
| \(2.74 \times 10^8\)                                       | 1.90              | 0.20   | 6                                        | 1                                                      |
| \(8.0 \times 10^8\)                                        | 8.47              | 0.16   | 9                                        | 2                                                      |
| \(8.0 \times 10^8\)                                        | 7.16              | 0.25   | 6                                        | 1                                                      |
Table 3. Results of external dose estimates among experimental rats during exposure to dispersed neutron-activated $^{56}$MnO$_2$ powder. The background dose has been subtracted

| Initial activity of sprayed $^{56}$MnO$_2$ powder, Bq | Tissue kerma, mGy | SD, mGy | Number of rats in each cage during exposure | Number of cages in the same external box during exposure |
|-----------------------------------------------------|------------------|---------|-------------------------------------------|--------------------------------------------------|
| $2.74 \times 10^8$                                  | 3.86             | 0.03    | 6                                         | 2                                                |
| $2.74 \times 10^8$                                  | 4.93             | 0.09    | 9                                         | 2                                                |
| $5.5 \times 10^8$                                   | 7.24             | 0.08    | 6                                         | 2                                                |
| $5.5 \times 10^8$                                   | 7.47             | 0.27    | 6                                         | 2                                                |
| $8.0 \times 10^8$                                   | 10.2             | 0.09    | 6                                         | 2                                                |
| $8.0 \times 10^8$                                   | 13.1             | 0.15    | 9                                         | 2                                                |

Fig. 3. External radiation doses of mice (mGy) depending on the activity of sprayed neutron-activated $^{56}$MnO$_2$ powder: comparison of the results of measurements.

Fig. 4. External radiation doses of rats (mGy) depending on the activity of sprayed neutron-activated $^{56}$MnO$_2$ powder: comparison of the results of measurements.

DISCUSSION

It is to note that the following sources of penetrating gamma irradiation are considered as external sources under conditions of exposure of experimental animals to sprayed radioactive powder: this is a sprayed $^{56}$MnO$_2$ powder distributed in the volume of a cage and the powder's microparticles trapped by the hair of animals on the surface of their body, as well as $^{56}$MnO$_2$ particles that have entered the animal's body and emitting gamma quanta that irradiate nearby animals. These sources of penetrating gamma radiation are forming the external absorbed dose, which is measured by the radiophotoluminescence glass dosimeters.

It should be pointed out that the values of external dose of gamma irradiation presented in Tables 2 and 3 and Figs 3 and 4 are the average dose for all experimental animals that were in the same cages during each exposure. Further, as noted in the Materials and Methods section, the absorbed dose measured by glass dosimeters was multiplied by the air kerma calibration factor and by the coefficient of conversion to tissue kerma.

It was found that the estimated absorbed dose of external gamma irradiation range about 1–15 mGy, which is order of magnitude less than the maximal internal absorbed whole body dose from gamma- and beta-irradiation of the same experimental animals irradiated under the same conditions (according to [14–16] the values of internal whole body gamma-beta irradiation dose range 330 mGy–1200 mGy for mice and 100 mGy–150 mGy for rats). It can be concluded that under the conditions of experiments with sprayed neutron-activated powder $^{56}$MnO$_2$, the internal gamma-beta irradiation of experimental animals is the main factor of radiation exposure in comparison with irradiation of laboratory mice and rats for various numbers of animals in cages.

With the same sprayed $^{56}$MnO$_2$ powder activity, the external absorbed dose is higher in situations when more experimental animals were placed in the cages (1), as well as when during exposure sessions two cages were placed side by side in one external box (2). The first circumstance can be explained by the fact that the more animals are in the cage, the more radioactive dust is retained by the hair on the surface of the animal's body, thereby creating a higher dose rate. The second circumstance can be explained by cross-irradiation from two adjacent cages with radioactive animals.
external gamma-irradiation. The results obtained are necessary for better understanding and interpretation of the observed biological effects of exposure to sprayed \(^{56}\text{MnO}_2\) microparticles \([1–3, 5–11]\). It would be important to support such interpretation by comparison of external absorbed dose with internal absorbed dose in the same experimental animals irradiated to sprayed \(^{56}\text{MnO}_2\) powder under the same conditions.

**ACKNOWLEDGMENTS**

We express our gratitude to Dr. Denis Dubov, Dr. Alexey Tishkin, Dr. Tatiana Lavrova, the personnel of the A. Tsyb Medical Radiological Research Center – Branch of the National Medical Research Center of Radiology of the Ministry of Health of the Russian Federation, who supported this research in a framework of the Institute’s Research Program AAAA-A18-118062590091-2 and in a framework of bilateral International Agreement on the scientific cooperation with Hiroshima University.

**AUTHOR CONTRIBUTIONS**

Conceptualization, M.H., H.S., and V.S.; data curation, V.S., H.S., N.F., Sh.T., S.E., A.K., S.I., and P.Sh.; formal analysis, V.S., M.H., H.S., N.K., A.K., S.I., and P.Sh.; funding acquisition, M.H.; investigation, V.S., H.S., N.Ch., D.Sh., A.A., K.Zh., A.P., T.K., V.B., and P.Sh.; methodology, H.S., V.S.; project administration, M.H.; resources, A.K., S.I., and P.Sh.; validation, S.E., Sh.T., and K.Sh.; writing—original draft preparation, V.S.; writing—review & editing, M.H. and V.S. All authors discussed the results and commented on the manuscript. All authors have read and agreed to the published version of the manuscript.

**FUNDING**

This work was supported by Grants-in-Aid for Scientific Research No. 26257501 and 19H01149, KAKENHI to M. Hoshi, Japan.

**SUPPLEMENT FUNDING**

This work was supported by JSPS KAKENHI Grant Number JP19H01149.

**CONFLICT OF INTEREST**

The authors declare that they have no conflicts of interest.

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