Supplementary information for Part 1

1. Table 1S: Dates of measurements, GPS coordinates, and levels of ^{137}Cs.
2. Fig. 1S: All the measured spectra.
3. A simple estimation of dose rate.

Table 1S List of the measurement points

The dates of the measurements, the GPS coordinates of the measurement points and ^{137}Cs levels in units of 1×10^4 Bq/m^2 are listed. The numbers in the first column correspond to those in Fig. 1 in the text. The data with an asterisk are published in our previous study [13]. Overall uncertainty in the values of the level is ±10% at most.

No	Longitude deg.	Latitude deg.	Meas.Date	^{137}Cs $\times10^4$ Bq/m^2
1	141.0501	37.4031	2019/07/13	0.7
2	141.0500	37.4029	2019/11/15	3.1
3	141.0422	37.3978	2019/11/15	4.5
4*	141.0500	37.3976	2017/12/09	2.6
5	141.0501	37.3976	2018/12/22	2.4
6	141.0501	37.3976	2019/07/13	2.2
7*	141.0418	37.3976	2017/06/17	3.5
8	141.0418	37.3976	2018/12/22	2.3
9*	141.0420	37.3973	2017/12/09	2.2
10	141.0500	37.3968	2019/11/15	1.2
11	141.0487	37.3911	2019/07/13	1.4
12	141.0486	37.3910	2018/05/12	2.5
13	141.0488	37.3869	2018/12/22	2.3
14	141.0488	37.3869	2019/07/13	2.6
15*	141.0487	37.3868	2017/12/09	2.0
16	141.0504	37.3718	2019/11/15	1.4
17	141.0550	37.3717	2018/05/12	1.1
18*	141.0468	37.3701	2016/07/16	4.2
19	141.0460	37.3603	2019/11/15	3.2
20*	141.0398	37.3428	2017/12/09	6.1
21	141.0398	37.3428	2018/12/22	3.3
22*	141.0399	37.3426	2016/07/16	2.2
23*	141.0399	37.3425	2017/06/17	2.5
24*	141.0398	37.3416	2016/05/21	2.7
25	141.0396	37.3411	2019/07/13	2.2
26	141.0537	37.3351	2019/07/13	1.0
27	141.0377	37.3349	2019/07/13	6.8
28	141.0533	37.3348	2018/05/12	1.5
29	141.0501	37.3334	2019/11/15	2.7
30*	141.0433	37.3317	2017/06/17	1.5
31	141.0433	37.3317	2019/07/13	5.1
32*	141.0434	37.3317	2016/05/21	2.7
33*	141.0434	37.3317	2016/07/16	1.4
34	141.0434	37.3317	2018/12/22	2.2
35*	141.0434	37.3313	2017/12/09	0.6
36	141.0340	37.3306	2018/07/14	3.4
37	141.0341	37.3306	2018/07/14	2.2
38	141.0342	37.3306	2018/07/14	3.3
39	141.0341	37.3304	2018/07/14	2.9
40	141.0342	37.3304	2018/07/14	4.9
41	141.0340	37.3303	2018/07/14	4.4
42*	141.0342	37.3302	2016/05/21	2.3
43	141.0349	37.3302	2019/11/15	2.1
44	141.0350	37.3302	2019/11/15	2.3
45*	141.0340	37.3301	2017/12/09	5.3
46	141.0340	37.3301	2018/12/22	2.7
47*	141.0342	37.3301	2017/06/17	2.7
48	141.0342	37.3301	2018/07/15	9.9
49	141.0342	37.3300	2018/12/22	6.5
50	141.0342	37.3300	2018/12/22	4.5
51*	141.0344	37.3299	2016/12/18	1.4
52	141.0329	37.3298	2018/07/14	4.1
53	141.0336	37.3275	2018/05/12	4.0
54*	141.0423	37.3152	2016/05/21	2.8

Fig. 1S All the measured spectra

A simple estimation of dose rate

When a gamma-ray beam of cross-section S travels a distance d through a medium, how much energy is absorbed by the medium?

E: energy of gamma ray.
ρ: bulk density of the medium.
$\mu_{en}(E)/\rho$: mass energy-absorption coefficient of the medium tabulated in Hubbell and Seltzer, 1995, p.84 for Cortical bone, p.100 for Skeletal muscle [1].
$Flux(E)$: scalar flux given by F4 tally of the present MCNP simulation in units of #/cm^2/s. Symbol # stands for the number of gamma rays whose energy is between E and E+dE, where dE is 0.35663 keV in the present simulation.

$I(E, d=0) = E\ S\ Flux(E)$: Beam intensity.
$I(E, d)$: Beam intensity after traveling d.
While traveling, the beam intensity decreases due to energy absorption by the medium.
$I(E, d) = I(E, d=0) \exp[-\mu_{en}(E)\ d]$.
With the use of an approximation: $\mu_{en}(E)\ d \ll 1$,

$$I(E, d) = I(E, d=0)\ [1 - \mu_{en}(E)\ d].$$

$\Delta\varepsilon$: Energy absorbed by the medium.

$$\begin{aligned}\Delta\varepsilon &= I(E, d=0) - I(E, d)\\ &= I(E, d=0)\ \mu_{en}(E)\ d\\ &= E\ S\ Flux(E)\ \mu_{en}(E)\ d\\ &= E\ Flux(E)\ \mu_{en}(E)\ S\ d\ \rho\ \rho^{-1}.\end{aligned}$$

Note that the mass of the medium M is $S\ d\ \rho$.
$\Delta\varepsilon = E\ Flux(E)\ \mu_{en}(E)\ M\ \rho^{-1}$.
Energy absorbed per unit mass of the medium is obtained as

$$\Delta\varepsilon/M = E\ Flux(E)\ \mu_{en}(E)\ \rho^{-1}. \qquad (1)$$

Estimation of dose rate for benthic organisms

In the present MCNP simulation, the volume tally F4, a sphere of 0.10m in diameter, is placed on the bottom. Therefore, the present *Flux*(E) is applicable only to benthic organisms which live in a region up to 0.1 m from the bottom. We take ICRU-44 Cortical bone and ICRU-44 Skeletal muscle as well-known substances for the numerical dose rate estimation.

In order to calculate eq. (1) numerically over the range between 20 keV and 662 keV, we divide the range into two parts, the first part where $\mu_{en}(E)\,\rho^{-1}$ decreases exponentially with the increase of energy and the second part where it varies little. The inflection point is easily recognizable by the visual inspection of the figures of $\mu_{en}(E)\,\rho^{-1}$ of the two materials depicted by Hubbell and Seltzer. In the first part, a simple exponential function, a exp(b E), is fitted to $\mu_{en}(E)\,\rho^{-1}$ tabulated by Hubbell and Seltzer, where a and b are parameters to be determined. In the second part, we set it constant.

For ICRU-44 Cortical bone, it is fitted in the energy range between 20 keV and 80 keV as shown in Fig. 1. In the second part between 86.5 keV and 662 keV, it is set constant 3.06×10^{-2} cm^2/g.

Cortical bone (ICRU-44)

ρ=1.92 g/cm^3

Energy(keV)	μ_{en}/ρ
20	3.601E+00
30	1.070E+00
40	4.507E-01
50	2.336E-01
60	1.400E-01
80	6.896E-02
100	4.585E-02

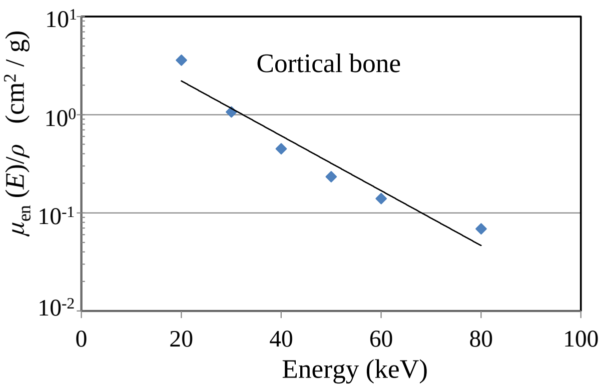

Fig. 1 Cortical bone

For ICRU-44 Skeletal muscle, a exp(b E) is fitted to $\mu_{en}(E)\,\rho^{-1}$ in the energy range between 20 keV and 60 keV as shown in Fig. 2. In the energy range between 56.9 keV and 662 keV, it is set constant 3.00×10^{-2} cm^2/g.

Skeletal muscle (ICRU-44)

ρ=1.05g/cm^3

Energy(keV)	μ_{en}/ρ
20	5.638E-01
30	1.610E-01
40	7.192E-02
50	4.349E-02
60	3.258E-02
80	2.615E-02
100	2.544E-02

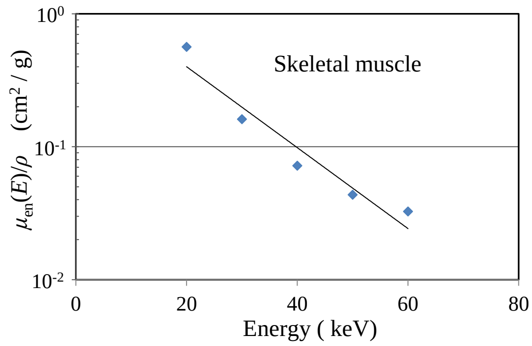

Fig. 2 Skeletal muscle

The approximated mass energy-absorption coefficients, $\mu_{en}(E)\,\rho^{-1}$, are shown in Fig. 3.

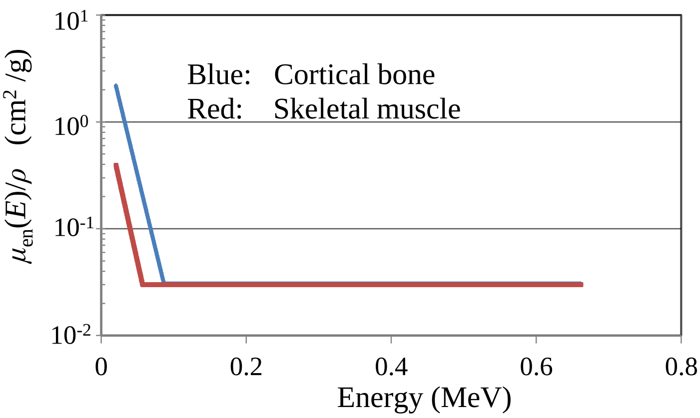

Fig. 3 Approximated mass energy-absorption coefficients

In Fig. 4 $E\ Flux(E)$ is plotted as a function of E. The source strength of the simulated $Flux(E)$ is described in the main text.

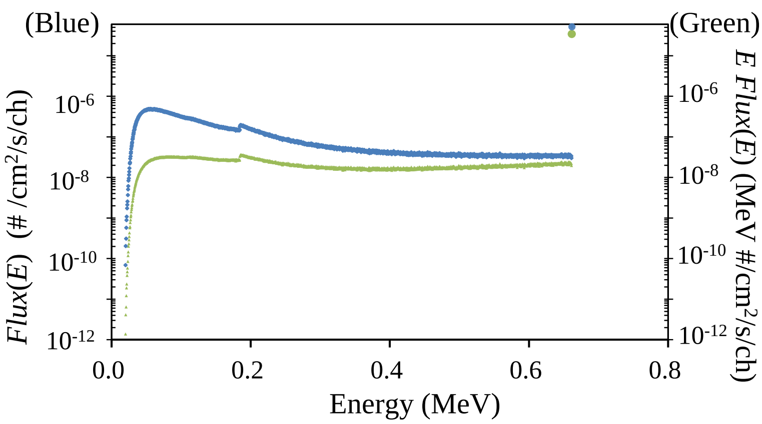

Fig. 4 $Flux(E)$ and $E\ Flux(E)$ as a function of E

$Flux(E)$ shown here is reproduced from Fig. 6 in the main text. Symbol # stands for the number of gamma rays in one channel, the width of which is 0.35663 keV.

The calculated results of $\Delta\mathcal{E}/M$ as a function of E are shown in Fig. 5.

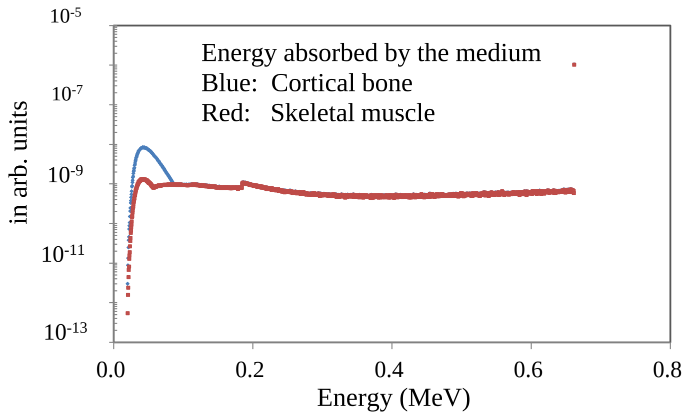

Fig. 5 $\Delta\varepsilon/M$ as a function of E

We sum up $\Delta\mathcal{E}/M$ from 20 keV to 662 keV to obtain the amount of energy absorbed by the medium in units of MeV/g/s. The results are 2.22×10^{-6} MeV/g/s for Skeletal muscle and 2.87×10^{-6} MeV/g/s for Cortical bone.

The output of the F6 tally gives energy absorbed by the medium in the tally. In the present simulation, the medium is water (ρ = 1.0 g/cm^3). The absorbed energy summed from 20 keV to 662 keV is 2.29×10^{-6} MeV/g/s, which is very close to the value for Skeletal muscle. According to Hubbell and Seltzer, the table and figure of $\mu_{en}(E)/\rho$ for water are very similar to those of Skeletal muscle. Therefore, the above results are quite reasonable.

For the sake of convenience, the source strength used in the simulation is 1 Bq / (π r^2), where r is the radius of the base of the cell cylinder, 50 cm. In order to match the source strength with the measured one, 1×10^5 Bq/m^2, the results are multiplied by (1×10^5 Bq/m^2) / (1 Bq /(π r^2)). Finally, taking into account the fact that in the case of ^{137}Cs (^{137m}Ba), the ratio of gamma-ray decay is 0.85 per decay, and using the relation, 1 MeV/g/s = 1.602×10^{-10} J/kg/s = 1.602×10^{-10} Gy/s, we get the dose rate, 0.085 μ Gy/h for Skeletal muscle, and 0.11 μ Gy/h for Cortical bone.

Reference

1. Hubbell J H, Seltzer S M (1995) Tables of X-ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients 1 keV to 20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest. NISTIR 5632. Natl. Inst. Standards Technol., USA. https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients (Accessed Jan. 7, 2024).