



Article Dose Rate Assessment Exercises with Stylized Phantom of Neon Flying Squid from Northwest Pacific

Jia Li 1,† , Wen Yu 2,3,*,† , Jianhua He 4 and Zhi Zeng 5,*

- ¹ College of Physics, Sichuan University, Chengdu 610065, China; lijia_17@163.com
- ² School of National Safety and Emergency Management, Beijing Normal University, Zhuhai 519087, China
- ³ Advanced Institute of Natural Sciences, Beijing Normal University, Zhuhai 519087, China
- ⁴ West China Hospital, Sichuan University, Chengdu 610041, China; hejianhuacd@163.com
- ⁵ Department of Engineering Physics, Tsinghua University, Beijing 100091, China
- * Correspondence: yuw@bnu.edu.cn (W.Y.); zengzhi@tsinghua.edu.cn (Z.Z.); Tel.: +86-597-3683506 (W.Y.); +86-10-62796715 (Z.Z.)
- + These authors contributed equally to this work.

Abstract: Radiation protection for non-human marine organisms still faces many challenges. To establish a more realistic radiation dosimetry model of cephalopods, this study developed a stylized phantom of neon flying squid (*Ommastrephes bartramii*) containing ten organs and tissues based on magnetic resonance imaging (MRI) technology. The internal and external dose conversion coefficients for eight radionuclides (134 Cs, 137 Cs, 131 I, 110m Ag, 60 Co, 54 Mn, 65 Zn, 95 Zr) of each organ/tissue were determined with Monte Carlo simulation using the Geant4 toolkit. Furthermore, with the reported coastal seawater radioactivity levels at the coastal area of Fukushima Daiichi Nuclear Power Plant after the accident in 2011 as the source term, the radiological dose rate for *O. bartramii* was evaluated with the stylized phantom developed in this study and with the conventional whole-organism ellipsoidal model in the ERICA Assessment Tool. Both results showed that the dose rate for *O. bartramii* derived from the FDNPP accident releases exceeded the generic no-effects screening benchmark level (10 μ Gy h⁻¹).

Keywords: stylized phantom; *Ommastrephes bartramii*; Geant4; dose conversion coefficient; Fukushima Daiichi Nuclear Power Plant accident

1. Introduction

In recent decades, the concept of environmental radiation protection has evolved from "... if man is adequately protected then other living things are also likely to be sufficiently protected" towards protecting the environment in an explicit sense, with the objective of avoiding detrimental effects within the environment [1–6]. In this context, we need a deeper understanding of dose–effect relationships and potential impacts to biota in radiation exposure scenarios, which likely requires more detailed dosimetric evaluations [7].

To establish a valid evaluation method for the impact of ionizing radiation on the ecosystem, the 15 countries of the European Commission (EC) launched the Framework for ASSessment of Environmental Impact (FASSET) project from 2000 to 2003. A corresponding radiation biological effect database has been established, in which thirty-one reference plants and animals were included. Additionally, calculation methods for estimating the internal and external exposure dose have been developed for various reference organisms [8]. Based on the FASSET project, to improve the evaluation method of the impact of ionizing radiation on the biological and ecological systems in the environment, the EC carried out the "Environmental Risk for Ionising Contaminants: Assessment and Management" (ERICA) (2004–2007) project, which provides a complete set of methods for environmental impact assessment, hazard characteristics, and management of ionizing radiation, including ERICA integrated approaches and the ERICA Assessment Tool [9].



Citation: Li, J.; Yu, W.; He, J.; Zeng, Z. Dose Rate Assessment Exercises with Stylized Phantom of Neon Flying Squid from Northwest Pacific. *J. Mar. Sci. Eng.* 2022, *10*, 782. https://doi.org/10.3390/ jmse10060782

Academic Editor: Gerardo Gold Bouchot

Received: 26 January 2022 Accepted: 30 May 2022 Published: 6 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). ERICA Tool is a computerized, flexible software system that assesses the radiological risk to biota in the environment with enhanced radioactive pollution (above the background values) [10,11]. The most recent update of the ERICA Tool is Version 2.0, which integrates the ICRP Biota DC software tool (Version 1.5.1) (The software developed on behalf of ICRP by A. Ulanowski and A. Ulanowski (Jr.)) [6] for the calculation of dose conversion coefficients (DCC) for user-defined organisms.

Furthermore, to enhance the capability of countries in the field of environmental radiation dose estimation, the International Atomic Energy Agency (IAEA) initiated the Environmental Modeling for Radiation Safety (EMRAS) research project (Phase I in 2003–2007, and Phase II in 2009–2011) and Modeling and Data for Radiological Impact Assessments (MODARIA) program (2012–2015). EMRAS focused on developing, comparing, and testing environmental assessment models used for estimating radiation exposure of humans and radiological impacts on flora and fauna due to actual and potential releases of radionuclides to the terrestrial and aquatic environment [4]. MODARIA continued some of the work of previous international exercises in the field of radioecological modeling and focused on areas where uncertainties remain in the predictive capability of environmental models [12]. The International Committee of Radiation Protection (ICRP) published a series of publications [13] providing more detailed technical requirements and references for the radiation protection system of non-human species.

Currently, ellipsoidal models with a uniform distribution of radionuclides are recommended by the ICRP and employed in the ERICA tool for estimating radiological dose to whole-organism non-human biota using Monte Carlo methods or analytical calculations. It is easy to use, generally conservative, and sufficient for a typical first-tier screening or environmental risk assessment.

In recent years, the development and use of more detailed, anatomically realistic dosimetric models has increased in radioecology, environmental radiation protection, and non-human biota radiological dosimetry research. Generally, the three main types of more refined or complex models include stylized phantoms, voxel phantoms, and hybrid or boundary representation (BREP) phantoms [7,14–17]. Stylized phantoms use multiple geometric shapes to represent key tissues and internal organs, so they are more physically representative than simple, uniform distribution, whole-body ellipsoidal models. Voxel phantoms, which are more realistic and representative, use tomography image acquisition techniques (e.g., CT and MRI) and associated software to define organ geometry in terms of a voxel matrix. The most advanced and realistic models are hybrid phantoms that utilize non-uniform rational B-spline (NURBS) or surface mesh techniques to develop a smooth and easy-to-manipulate surface boundaries to represent the geometry of the organism. Compared to the uniform ellipsoidal models, these refined complex models not only improve the accuracy in anatomical geometry, but also allow organ-specific dose assessment or radionuclide uptake research. Many stylized, voxel or hybrid phantoms were developed recently, most of which are for ICRP Reference Animals and Plants (RAPs). Martinez et al. developed stylized and voxel phantoms for rainbow trout and estimated the absorbed radiation dose and dose rates for each organ from ¹³¹I uptake in these phantoms [18].

Higley et al. created a voxel phantom of ICRP crab, obtained the absorption score of electrons and photons, and reinforced the well-understood relationship between the absorbed fraction (AF) and the target's mass and location [19]. Caffrey et al. created a voxel phantom of adult and juvenile rabbits with CT images to study the effects of biological composition and density on AF, as well as different organ doses at different life-stages [20]. Kinase built a voxel model for frog and confirmed that the voxel-based phantom is useful for organ dose evaluation [21]. Segars et al., Stabin et al., and Martinez et al. developed hybrid phantoms for mouse, beagle dog, and rainbow trout [22–24]. To our knowledge, advanced models, such as stylized phantom or voxel phantom, for cephalopods have not been established or reported in the literature.

It has also been well recognized that each type of phantom has its associated advantages and/or disadvantages. Although voxel and hybrid phantoms are more realistic and anatomically accurate, the development process for them is very time-consuming [7,14]. It is recommended to use a fit-for-purpose approach when using different types of models of varying degrees of complexity for different applications, which has long been employed in human radiation protection [7].

Ommastrephe bartramii (neon flying squid) is a squid species that is commercially important, commonly consumed by humans, and widely migratory in the Pacific Ocean and circumglobally in temperate and tropical waters. It feeds near the surface on small fish and is thus a potential accumulator of radionuclides via diet and water pathways. Moreover, like other cephalopods, neon flying squid have a strong capability to accumulate silver in their bodies, so it will be a good indicator for the ^{110m}Ag released from the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident [25,26]. In this study, the authors attempt to establish the first stylized phantom for *O. bartramii*.

First, based on Magnetic Resonance Imaging (MRI) techniques, the authors built the stylized phantom of squid, which substantially improved the precision of the existing phantom, which is a geometric phantom, and using ellipsoids to describe the shape of the organism. Second, the dose conversion coefficients (DCCs) of the stylized phantom are calculated using Monte Carlo simulation. Then, the radiological dose rate of the squid was evaluated with the DCCs and the reported radionuclide concentrations at the coastal area of FDNPP. Finally, the results generated with the model in this study were analyzed and compared to the calculated results with the ERICA Tool (Version 2.0).(The ERICA Tool is maintained by a consortium led by the Norwegian Radiation and Nuclear Safety Authority (DSA). You can sign up for a free download on its website (https://erica-tool.com/) (accessed on 29 May 2022).

2. Materials and Methods

2.1. Scanning and Segmentation of the Sample

The sample used in this study is a neon flying squid captured with fishhook from the northwestern (NW) Pacific. This squid was 25 cm long, weighed 1200 g and had not reached sexual maturity. The squid was frozen at sea immediately after capture and was thawed at the land-based lab, just prior to imaging.

In the previous studies, phantoms were created using tomography images obtained with either the CT technique or MRI technique [27,28]. Considering that MRI has a much better resolution in imaging soft tissues, this study performed the MRI scan at the Department of Radiology, Xiamen Second Hospital. In the MRI scan, the slicing thickness was set to be 6 mm, and 12 slices were obtained and preserved as a 512-by-512-pixel image. Figure 1 depicts one of the MRI images.



Figure 1. One of the MRI scan images.

To create a more realistic geometry for a stylized phantom, individual organs are contoured on each MRI image in a segmentation process. The MRI tomography images were read with MATLAB (R2018b) to identify the gray scales of each pixel (512×512) [29].

Then, since the densities in different organs/tissues are very similar, the tomography images had to be manually contoured into different organs, including head, foot, carcass, gladius, ink-sac, stomach, liver, gill, and glands, with consideration of gray scales, squid anatomy, spatial textures, and geometric shapes [30]. In this study, it is difficult to distinguish the gonad of the sample because it has not yet become sexually mature.

Considering that the gonad is one of the most radiologically sensitive organs of an organism, it is necessary to include this important organ in this study. Therefore, the authors set up the stylized phantom of the gonad with a size of 0.62cm $\times 0.62$ cm $\times 0.62$ cm, referring to the size of the gonad in a 25 cm fish [31].

2.2. Stylized Phantom Establishment

The more detailed and realistic a phantom's shape is, the more accurate the dose rate calculation is and the more time-consuming the phantom establishment procedure is. Generally, there are three kinds of phantom that are used in marine organism dose rate calculation: geometric phantom, stylized phantom, and voxel phantom. The geometric phantom is the simplest one, which simplifies the marine organism into one ellipsoid. It requires the smallest workload, but the uncertainty of the calculated dose rate is large in some cases [19]. Some scholars have used the geometric phantom in dose studies on squids. The ERICA Assessment Tool developed in the ERICA Project of EC also uses geometric phantom. In the stylized phantom is a more detailed model compared to the geometric phantom. In the stylized phantom, the location and size of the organs were determined by matching their stylized shapes and locations based on CT or MRI slices. The voxel phantom is the most detailed and time-consuming model constructed with a series of image slices formatted in pixels with a given thickness, forming a volume pixel unit, or voxel unit.

Based on the scanning and segmentation in Section 2.1, a stylized phantom was established with the information of sizes, shapes, and positions of the organs displayed in slices for the following Monte Carlo simulation. The geometry parameters of each organ of the sample were determined according to the size, shape, and location of each organ in the segmented MRI images (Figure 2a). The stylized phantom of a squid with internal organs and tissues was then established with Geant4 software, as shown in Figure 2b,c. The elemental composition of each organ in the stylized phantom established in this study are shown in Table 1 [31]. The geometric parameters and the densities of the organs were listed in Table 2.



Figure 2. (**a**) A segmented MRI image of *O. bartramii*; (**b**) the front image of the stylized model; (**c**) the side image of the stylized model.

Organs	Elements (%)										
	С	Н	0	Ν	Ca	Na	Mg	Р	S	Cl	К
Carcass	14.3	10.2	71.0	3.4	_	0.1	_	0.2	0.3	0.1	0.4
Foot	14.3	10.2	71.0	3.4	_	0.1	_	0.2	0.3	0.1	0.4
Head	14.3	10.2	71.0	3.4	_	0.1	_	0.2	0.3	0.1	0.4
Gladius	15.2	3.0	41.8	2.5	21.0	3.5	0.2	10.3	0.3	_	2.2
Ink-sac	10.5	10.3	74.9	3.1	_	0.2	_	0.2	0.3	0.3	0.2
Stomach	12.1	10.3	73.4	3.2	_	0.1	_	0.2	0.2	0.3	0.2
Liver	13.2	10.2	72.4	3.0	_	0.2	0.3	0.2	0.2	0.2	0.1
Gill	10.5	10.3	74.9	3.1	_	0.2	_	0.2	0.3	0.3	0.2
Glands	10.1	9.1	69.0	11.0	_	0.2	0.1	0.2	0.1	0.1	0.1
Gonad	11.5	10.6	75.1	2.2	_	0.1	_	0.1	0.1	0.2	0.1

Table 1. Elemental composition of the organs in the O. bartramii sample [31].

Table 2. Geometry, mass, and density information of O. bartramii.

Organs	Geometry	a1, b1, c1	r1	h, r2	a2, b2, c2	Density	Weight Coefficients
Carcass	ellipsoid	13.4, 4.5, 3.5	_	_	_	1.020	0.699
Foot	cylinder	_	_	6.5, 1.8	_	1.025	0.053
Head	cylinder	_	_	6.0, 3.1	_	1.020	0.143
Gladius	cuboid	_	_	_	13.0, 3.0, 0.2	1.200	0.007
Ink-sac	ellipsoid	6.0, 1.2, 1.0	_	_	_	1.040	0.024
Stomach	ellipsoid	3.3, 1.4, 1.3	_	_	_	1.030	0.020
Liver	ellipsoid	4.7, 1.9, 1.0	_	_	_	1.030	0.030
Gill	ellipsoid	4.6, 1.3, 0.8	_	_	_	1.200	0.019
Glands	sphere	_	1.25	_	_	1.000	0.004
Gonad	sphere	_	0.62	_	_	1.000	0.001

The parameters a1, b1, and c1 represented semi-axis lengths of ellipsoid; for sphere geometry, the parameter r1 represent the radius; for cylinder geometry, the parameters h and r2 represent the height and base-radius; for cuboid geometry, the parameters a2, b2, and c2 represent lengths, height, and width. The unit of lengths, heights, and width is 'cm' and the unit of density is 'g cm^{-3'}.

2.3. Source Term

Considering the half-life, characteristic energy, and released amount both in the accidental and regular scenario of the radionuclides [32], eight artificial radionuclides (⁵⁴Mn, ⁶⁰Co, ⁶⁵Zn, ⁹⁵Zr, ^{110m}Ag, ¹³¹I, ¹³⁴Cs, and ¹³⁷Cs) were considered in this study.

Since the traveling distance of the particles in seawater is usually short, it is reasonable to take the radionuclides in a seawater sphere surrounding the squid as the source terms in the dose rate simulation to reduce the computing time. After many pilot simulations, it was found that the typical traveling distances of the eight radionuclides were less than 1 m, so the radius of the source term seawater sphere was set to be 1.2 m. The elemental composition and density of seawater used in the simulation are shown in Table 3 [32]. In the simulation, it is assumed that the radionuclides were evenly distributed in the seawater sphere (R = 1.2 m) surrounding the squid, and evenly distributed in the organs or tissues inside the squid.

Table 3. Elemental composition and density of seawater used in simulation [32].

Element	Н	0	Na	Cl	Mg	S	Ca	К
Mass fraction	10.756	86.045	1.056	1.851	0.126	0.087	0.040	0.039
Density (g cm $^{-3}$)				1.0)25			

2.4. Dose Conversion Coefficient Simulation

In this study, the radiological dose conversion coefficients (DCCs) were determined with Monte Carlo simulations using the Geant4 toolkit.

Geant4 is a Monte Carlo simulation toolkit developed by the European Organization for Nuclear Research (CERN) for the simulation of the interaction between particles and materials [33]. The standard electromagnetic physics software package of Geant4 was employed in this study to perform particle transport simulation and to derive absorbed energy fraction of the injecting particles. For beta decay or electron emitting, the source particle was set as electron. The energy was set as the average energy of beta or monoenergetic electron. For X- or gamma-ray, the source particle was set as photon with its characteristic energy.

DCC is the mean absorbed dose rate (μ Gy h⁻¹) per unit activity concentration of an organism (Bq kg⁻¹ fresh weigh) or per unit activity concentration of the environmental medium (Bq kg⁻¹ wet weight) [34]. The radiological DCCs were calculated with the deposited energy of injecting particles in organisms. Therefore, DCCs are specific to the defined organism geometry, elemental composition, and densities in tissues, organs, and surrounding media, radiation type, and energies, etc. The DCC of radionuclide i, organ j(DCCi,j) is defined as follows:

$$DCC_{i,j} = c \cdot E_{k,i} \times P_i \times M/m \tag{1}$$

where c is a constant of unit conversion factor, $c = 5.76 \times 10^{-4} (\mu Gy \text{ Kg Bq}^{-1} \text{ h}^{-1} \text{ Mev}^{-1})$ [32]; $E_{k,i}$ is the deposited energy of the radionuclide i (MeV) which is generated by simulation with Geant4; P_i is the emitting probability of the radionuclide i; and M and m is the mass of the source and the organs, respectively.

2.5. Radiological Dose Assessment

The dose rate (Di) received by the organism could be divided into two parts, the one from the radionuclides in the seawater, and the one derived from the activity concentrations of the organs in the organism [35]. The former part is the external dose rate, and the latter part is the internal dose rate. Therefore, the total radiological dose rate could be expressed as follows:

$$D_{i} = \sum_{j} C_{\text{org}}, i, j \times \text{DCC}_{\text{int}, i, j} + C_{\text{sea}, i} \times \text{DCC}_{\text{ext}, i}$$
(2)

where $DCC_{ext,i}$ is the external DCC of radionuclide I; $DCC_{int,i,j}$ is the internal DCC of radionuclide i, organ j; $C_{org,i,j}$ (Bq Kg⁻¹) is the activity of radionuclide i in the unit mass of organ j; and $C_{sea,i}$ (Bq L⁻¹) is the activity of radionuclide i in the unit volume of seawater.

The concentration factor (CF) is the ratio of the concentration of a specific radionuclide in the organ to the activity concentration of the same radionuclide in the seawater [34]. Assuming a steady-state situation, where the radionuclides have reached equilibrium concentration between the environmental medium and the body of the organism, the CF could be calculated as:

$$F = C_{\rm org} / C_{\rm sea} \tag{3}$$

The dose rate (D_i) received by the organism could be further expressed as:

C

$$D_{i} = C_{sea}(DCC_{int,i}/CF + DCC_{ext,i})$$
(4)

The CF values of the squid used in this paper are shown in Table 4. The relevant IAEA Technical Reports Series No. 422 have entries for ^{110m}Ag and ¹³¹I uptake in the mollusk category (60,000 and 10 L Kg⁻¹, respectively), but none specifically for squid/cephalopods.

Table 4. The CFs of Cephalopods and Mollusks [34,36].

CF(L Kg ⁻¹)	⁵⁴ Mn	⁶⁰ Co	⁶⁵ Zn	⁹⁵ Zr	^{110m} Ag	¹³¹ I	¹³⁴ Cs	¹³⁷ Cs
Cephalopods	3000	300	60,000	50	_	_	9	9
Mollusks	_	_	_	-	60,000	10	_	_

Therefore, in the calculation, the CFs for 110mAg and 131I in mollusk were used.

3. Result and Discussion

3.1. Dose Conversion Coefficient of Individual Organs Obtained with Geant4

In this work, eight radionuclides (⁵⁴Mn, ⁶⁰Co, ⁶⁵Zn, ⁹⁵Zr, ^{110m}Ag, ¹³¹I, ¹³⁴Cs, and ¹³⁷Cs) were used as the source terms in the simulation, because they have a relatively large fission yield, higher energy, and/or longer half-lives compared to the other radionuclides released from the accident, and they are more likely to have negative effects on the marine ecosystem.

For the sake of being consistent with ERICA, we assume that the radiation source is evenly distributed throughout the organism during internal irradiation. Tables 5 and 6 show the external and internal DCCs of the squid organs, derived from the deposited energy from both the external and internal sources with Geant4, respectively.

Nuclides	$DCCs imes 10^{-4}$ ($\mu Gy Kg h^{-1} Bq^{-1}$)									
	Carc	Foot	Head	Glad.	Ink-s.	Stom.	Liver	Gill	Glands	Gona.
¹³⁷ Cs	2.67	1.66	2.25	1.82	1.89	1.68	1.92	1.80	1.88	2.03
^{110m} Ag	2.99	1.89	2.45	1.96	2.01	1.83	2.06	1.97	2.04	1.97
⁶⁰ Co	5.96	3.74	4.89	2.92	4.22	3.74	4.32	4.04	4.14	4.69
¹³⁴ Cs	2.81	1.80	2.42	2.01	1.95	2.00	2.12	1.76	1.93	1.85
^{131}I	1.54	0.89	1.28	1.43	1.05	1.03	1.08	9.90	1.06	0.92
⁵⁴ Mn	3.89	2.45	3.25	2.29	2.76	2.27	2.75	2.44	2.65	2.54
⁶⁵ Zn	2.55	1.58	2.14	1.28	1.73	1.63	1.81	1.76	1.84	1.48
⁹⁵ Zr	1.96	1.16	1.63	1.17	1.34	1.10	1.41	1.24	1.30	1.47

 Table 5. External dose conversion coefficient of squid organs.

 Table 6. Internal dose conversion coefficient of squid organs.

Nuclides	$DCCs imes 10^{-4}$ ($\mu Gy~Kg~h^{-1}~Bq^{-1}$)									
	Carc	Foot	Head	Glad.	Ink-s.	Stom.	Liver	Gill	Glands	Gona.
¹³⁷ Cs	3.74	3.06	3.62	2.53	3.37	3.16	3.40	3.20	3.43	2.97
^{110m} Ag	1.21	0.88	1.08	0.83	0.95	0.9	0.96	0.92	0.96	0.88
⁶⁰ Co	3.97	3.06	3.68	2.51	3.35	3.15	3.37	3.20	3.38	2.97
¹³⁴ Cs	3.59	2.79	3.46	2.22	3.17	2.90	3.22	2.96	3.24	2.66
^{131}I	3.68	2.99	3.61	2.44	3.36	3.12	3.40	3.17	3.45	2.91
⁵⁴ Mn	1.16	0.71	0.98	0.59	0.08	0.75	0.82	0.76	0.83	0.7
⁶⁵ Zn	0.81	0.49	0.69	0.37	0.57	0.53	0.58	0.53	0.58	0.5
⁹⁵ Zr	1.83	1.50	1.74	1.30	1.63	1.54	1.63	1.56	1.64	1.48

In the case of external exposure, for the same organ, the DCC of ⁶⁰Co is the largest, while the DCC of ¹³¹I is the smallest, and the DCCs of radionuclides are in positive correlation with the energy of the emitting particles of the radionuclides, because the particles with higher energy travel further in seawater and have a larger probability of depositing energy in the organism. In the case of internal exposure, the DCCs of beta-emitting radionuclides are larger than that of gamma-emitting radionuclides, because the mean free path of electrons is shorter than that of photons, resulting in larger probabilities of depositing energy inside the organ. For the same radionuclide in the source term radionuclide, the organs with higher density have higher DCCs, indicating a larger deposited energy.

3.2. Comparison of DCCs Obtained with Geant4 and the ERICA Tool

In order to verify the result simulated with the model developed in this study, DCCs of the sample obtained with the stylized model were compared to those generated with the ERICA Tool. The ERICA Tool is a software system for biological radiological risk evaluation. It uses the ellipsoid geometric phantom to describe the shape of the marine organism, and it does not consider the internal structure of the creature but assumes that

the radionuclides are distributed evenly inside the body of the organism. Therefore, the ERICA Tool can only calculate the DCCs for the whole body of the sample but not the DCCs of individual organs.

Tier 2 assessment in ERICA (Version 2.0) was used to evaluate the dose rate of the sample squid with the same source term and compared it with the Geant4 simulation results in this study. Since there is no cephalopod model built in ERICA, the authors used the "Add organism" function to build an ellipsoid model for the sample. The ellipsoid's length, width, and height were set as the measured length, width, and height of the sample, respectively. However, the density of the ellipsoid model was set to be 1 g cm⁻³, which is default and could not be changed in ERICA. The other parameters used in the calculation, such as the CFs, Distribution Coefficient (Kds), and the weighing factors, were set to be the default values in the ERICA Tool.

In order to compare the DCCs for the whole body obtained with the ERICA Tool and the DCCs of individual organs obtained with Geant4, the DCCs of individual organs obtained with Geant4 need to be converted into DCCs for the whole body. The DCCs for the whole body could be expressed as the summation of the multiplications of the relevant weight coefficient (w_i) of each organ and the external and internal DCCs.

$$DCC = \sum_{i=1}^{10} DCC_i \times w_i$$
(5)

The DCCs generated with the ERICA Tool and converted DCCs generated with Geant4 are listed in Table 7.

Table 7. Internal and external dose conversion coefficients of whole-body *O. bartramii* obtained with the ERICA tool and Geant4.

Nuclides	DCCs $ imes$ 10 $^{-4}$ (μ Gy Kg h $^{-1}$ Bq $^{-1}$)									
	¹³⁷ Cs	^{110m} Ag	⁶⁰ Co	¹³⁴ Cs	¹³¹ I	⁵⁴ Mn	⁶⁵ Zn	⁹⁵ Zr		
Ext-ERICA	2.90	1.42	13.00	7.99	1.95	4.30	3.01	3.80		
Int-ERICA	1.78	2.18	1.96	1.92	1.36	0.55	0.40	1.14		
Ext-Geant4	2.47	2.75	5.49	2.61	1.42	3.58	2.35	1.80		
Int-Geant4	3.64	1.14	3.80	3.47	3.59	1.05	0.75	1.77		

In this study, the weight coefficients of each organ were listed in Table 2. For external exposure, the calculated DCCs by ERICA are larger than Geant4. For internal exposure, the calculated DCCs using the ERICA Tool are smaller than those calculated using Geant4. The reasons for this discrepancy may be multifaceted. First, it is related to differences in the density of the models. In the ERICA Tool, the densities of an organism and the surrounding medium (seawater) are set to be 1 g cm $^{-3}$, while the densities of modeled organs/tissues and seawater in Geant4 were set as the realistic values, which are all greater than 1 g cm $^{-3}$. Therefore, even though both models in the ERICA Tool and Geant4 were of the same size, the mass and density of the model in Geant4 were greater than those in ERICA. For internal exposure, DCC is the proportion of energy absorbed by the radiation source in an organ or organism. Larger density will lead to larger internal DCCs, since more energy is likely to deposit inside the organism. In contrast, for external exposure, the density of seawater set in ERICA is less than that in GEANT4, which means that emitting particles from the seawater travel further in ERICA's model, resulting in larger external DCCs from ERICA than those from Geant4. The second reason for the discrepancy in DCCs is that the elemental composition of the organism's tissues in the two models is inconsistent, which leads to inconsistent absorption of radiation by biological tissues, resulting in different DCCs.

3.3. Dose Rate for the Squid Sample in the FDNPP Accident Scenario

The FDNPP Accident in 2011 released a large amount of radionuclide into the marine environment and raised broad concern on seafood safety and environmental safety. In order to evaluate the radiological impact of the accident on marine species and to be more conservative, the maximum radioactivity values of ¹³⁴Cs, ¹³⁷Cs, and ¹³¹I reported in literature in the coastal seawater after the accident were used as the source term in the simulation [32]. The released amount of other radionuclides (⁵⁴Mn, ⁶⁰Co, ⁶⁵Zn, ⁹⁵Zr, ^{110m}Ag) was much lower than that of ¹³⁴Cs, ¹³⁷Cs, and ¹³¹I, and the radioactivity levels of these radionuclides have not been reported. Therefore, in this scenario, these radionuclides are ignored in the source term.

The dose rates for the squid sample in the FDNPP accident scenario calculated with the ERICA Tool and Geant4 simulations with the voxel squid model in this study are listed in Table 8. With the maximum reported activity concentration in coastal seawater after the FDNPP accident as the source term, the radiological dose rate for the squid sample simulated with the ERICA Tool is 581 μ Gy h⁻¹, and the one simulated with the stylized model established in this study is 1140 μ Gy h⁻¹. The two results are of the same order of magnitude, indicating that the stylized model is reliable and reasonable.

_					
	Nuclide	Max-Radio [14]	ERICA	This Study	Recommended-EC
			Tool	l	
	¹³⁴ Cs	6.70 imes 104	1.70 imes 102	$2.39\times10^2\pm0.85$	_
	¹³⁷ Cs	6.80 imes 104	1.30 imes 102	$2.27\times10^2\pm0.85$	_

2.81 imes 102

 5.81×102

 Table 8. Radiation dose rates simulated by the ERICA tool and Geant4.

 1.80×105

[']Max-radio' is Maximum radioactivity(Bq L⁻¹) in coastal seawater at FDNPP in 2011; 'Erica Tool' and 'This study' refer to their simulated radiological dose rate (μ Gy h⁻¹); 'Recommended-EC' refers to recommended screening dose rate by European Commission.

 $6.71\times10^2\pm1.14$

 $1.14 \times 10^{3} \pm 1.66$

10

Both simulated dose rate results, with the ERICA Tool and with the stylized model developed in this study, are one magnitude higher than the screening benchmark level $(10 \ \mu\text{Gy} \ h^{-1})$ recommended by the EC [37], indicating that the squid in this scenario might be at risk and require further study. However, there is very little literature on the radiobiological impact on cephalopods. The relevant research work on the fish shows that the fish received the same dose rate as the calculated dose rate result in this study and suffers from adverse effects on reproduction, such as delayed spawning and decreased testicular quality [38].

4. Conclusions and Prospect

131_I

Total

This study developed the first stylized phantom with internal organs and tissues of *O. bartramii* from the NW Pacific based on an MRI technique. The DCCs of individual organs and tissues were simulated with the Monte Carlo method and Geant4 toolkit. With the maximum reported radioactivity levels in coastal seawater of FDNPP after the accident in 2011 as the source term, the dose rates received by the neon flying squid sample were simulated with the stylized phantom developed in this study and the geometric model of the ERICA Tool. Both simulated dose rate results are compatible, indicating that the stylized phantom developed in this study is reasonable and reliable.

In this study, it was not possible to obtain the CFs in individual organs and tissues, so the average CFs in the whole body were used in the assessment. With the CFs in individual organs and tissues, it is possible to obtain a more realistic and detailed simulated dose rate with the stylized phantom developed in this study.

Compared with the geometric model and the voxel model, the stylized phantom reaches the best balance of workload and precision, and it can provide the radiological dose rate for each individual organ and assess each organ's contribution to the whole-body dose. Therefore, it is expected to be the best choice for non-human species radiological dose evaluation. In addition, a fit-for-purpose approach is recommended when researchers choose the type of phantom models in evaluation.

We recommend using ERICA as a screening tool to evaluate the necessity of building a phantom, as well as which model is the most suitable. If the dose rate generated with ERICA is far lower than the screening benchmark level, it is recommended that there is no need to build more advanced phantoms for the general assessment objectives. If the assessment result from ERICA is close to or exceeding the screening benchmark level, it is recommended to build advanced phantoms to reveal the dose rates to individual organs/tissues. It is also recommended to choose the type of phantom model, taking into account the purpose of the assessment, as well as time costs and manpower costs, as the fit-for-purpose approach has long been used in human radiation protection.

Author Contributions: Conceptualization, J.L. and W.Y.; methodology, J.L. and W.Y.; software, J.L.; validation, J.L., W.Y. and Z.Z.; formal analysis, W.Y.; investigation, J.H.; resources, J.H.; data curation, J.L.; writing—original draft preparation, J.L.; writing—review and editing, W.Y.; visualization, J.H.; supervision, W.Y.; project administration, Z.Z.; funding acquisition, W.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (Grant No. 12105378), the Talented Research Start-up Project Grant of Zhuhai Campus, Beijing Normal University, the Coordinated Research Project (IAEA/CRP K41017) and Regional Cooperative Agreement Project (IAEA/RCA RAS7028) of the International Atomic Energy Agency (IAEA).

Institutional Review Board Statement: This study complied with all relevant legislation, used minimum number of samples and minimized the harm to animals.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://pan.baidu.com/s/1GBKIMNle2Tgw9l6ohoGkAg?pwd=cwp5 (accessed on 29 May 2022).

Acknowledgments: We would like to thank Jianmin-Zhuang, chief physician of Xiamen Haicang hospital, for providing the scanning for this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

- 1. ICRP. Recommendations of the international commission on radiological protection. *Ann. ICRP* **1977**, *1*, 1–53.
- 2. ICRP. A framework for assessing the impact of ionizing radiation on non-human species. Ann. ICRP 2003, 33, 1–6.
- 3. ICRP. The 2007 recommendations of the international commission on radiological protection. Ann. ICRP 2007, 37, 2–4.
- 4. ICRP. Environmental Protection: The Concept and Use of Reference Animals and Plants. Ann. ICRP 2008, 38, 4–6.
- Clement, C.H.; Strand, P.; Beresford, N.; Copplestone, D.; Godoy, J.; Jianguo, L.; Saxén, R.; Yankovich, T.; Brown, J. Environmental protection: Transfer parameters for reference animals and plants. *Ann. ICRP* 2009, *39*, 6. [CrossRef]
- 6. ICRP. Dose coefficients for non-human biota environmentally exposed to radiation. Ann. ICRP 2017, 46, 1–136. [CrossRef]
- Montgomery, D.A.; Martinez, N.E. Dosimetric modeling of Tc-99, Cs-137, Np-237, and U-238 in the grass species Andropogon Virginicus: Development and comparison of stylized, voxel, and hybrid phantom geometry. J. Environ. Radioact. 2020, 211, 106075. [CrossRef]
- 8. Williams, C. Framework for assessment of environmental impact (FASSET) of ionising radiation in European ecosystems. J. Radiol. Prot. 2004, 24, A1–A12.
- Brown, J.E.; Alfonso, B.; Avila, R.; Beresford, N.A.; Copplestone, D.; Proehl, G.; Ulanovsky, A. The ERICA Tool. J. Environ. Radioact. 2008, 99, 1371–1383. [CrossRef]
- 10. Pappa, K.F.; Tsabaris, C.; Ioannidou, A.; Patiris, L.D.; Kaberi, H. Radioactivity and metal concentrations in marine sediments associated with mining activities in Ierissos Gulf, North Aegean Sea, Greece. *Appl. Radiat. Isot.* **2016**, *116*, 22–33. [CrossRef]
- Pappa, K.F.; Tsabaris, C.; Patiris, L.D.; Androulakaki, E.G.; Vlastou, R. Historical trends and assessment of radionuclides and heavy metals in sediments near an abandoned mine, Lavrio, Greece. *Environ. Sci. Pollut. Res.* 2018, 25, 30084–30100. [CrossRef] [PubMed]
- Johansen, M.; Beresford, N.A.; Howard, B.; Hinton, T.; Bollhoefer, A.; Doering, C.; Twining, J. Recent developments in the modelling of radionuclide uptake, radiation dose and effects in wildlife. In Proceedings of the 13th South Pacific Environmental Radioactivity Association Conference (SPERA 2014), Darwin, Australia, 1–5 September 2014.

- 13. ICRP. Protection of the environment under different exposure situations. ICRP Publication 124. Ann. ICRP 2014, 43, 2.
- 14. Zaidi, H.; Tsui, B. Review of Computational Anthropomorphic Anatomical and Physiological Models. *Proc. IEEE*. 2009, 97, 1938–1953. [CrossRef]
- 15. Martinez, N.E. Review of current methods in internal dosimetry of non-human biota. In Proceedings of the 15th International High-level Radioactive Waste Management Conference, Charleston, SC, USA, 12–16 April 2015.
- 16. Xie, T.; Zaidi, H. Development of computational small animal models and their applications in preclinical imaging and therapy research. *Med. Phys.* **2016**, *43*, 111–131. [CrossRef] [PubMed]
- 17. Zaidi, H. Computational Anatomical Animal Models; IOP Publishing: Bristol, UK, 2018; pp. 2053–2563.
- Martinez, N.E.; Johnson, T.E.; Capello, K.; Prinder, J.E. Development and comparison of computational models for estimation of absorbed organ radiation dose in rainbow trout (oncorhynchus mykiss) from uptake of iodine-131. *J. Environ. Radioact.* 2014, 138, 50–59. [CrossRef] [PubMed]
- 19. Caffrey, E.A.; Higley, K.A. Creation of a voxel phantom of the ICRP reference crab. J. Environ. Radioact. 2013, 120, 14–18. [CrossRef]
- Caffrey, E.A.; Johansen, M.P.; Higley, K.A. Voxel modeling of rabbits for use in radiological dose rate calculations. J. Environ. Radioact. 2015, 151, 480–486. [CrossRef]
- 21. Kinase, S. Voxel-based frog phantom for internal dose evaluation. J. Nucl. Sci. Technol. 2008, 45, 1049–1052. [CrossRef]
- Segars, W.P.; Tsui, B.M.W.; Frey, E.C.; Johnson, G.A.; Berr, S.S. Development of a 4-D digital mouse phantom for molecular imaging research. *Mol. Imaging Biol.* 2004, 6, 149–159. [CrossRef]
- Stabin, M.G.; Kost, S.D.; Segars, W.P.; Guilmette, R.A. Two realistic beagle models for dose assessment. *Health Phys.* 2015, 109, 198–204. [CrossRef]
- 24. Martinez, N.E.; Johnson, T.E.; Pinder, J.E. Application of computational models to estimate organ radiation dose in rainbow trout from uptake of molybdenum-99 with comparison to iodine-131. *J. Environ. Radioact.* **2016**, *151*, 468–479. [CrossRef] [PubMed]
- Bustamante, P.; Teyssie, J.L.; Danis, B.; Fowler, S.W.; Miramand, P.; Coeret, O.; Warnau, M. Uptake, transfer and distribution of silver and cobalt in tissues of the common cuttlefish sepia officinalis at different stages of its life cycle. *Mar. Ecol. Prog.* 2004, 269, 185–195. [CrossRef]
- 26. Miramand, P.; Bentley, B. Concentration and distribution of heavy metals in tissues of two cephalopods, eledone cirrhosa and sepia officinalis, from the french coast of the english channel. *Mar. Biol.* **1992**, *114*, 407–414. [CrossRef]
- Cannon, M.E.; Carpenter, S.L.; Elta, G.H.; Nostrant, T.T.; Scheiman, J.M. Eus compared with ct, magnetic resonance imaging, and angiography and the influence of biliary stenting on staging accuracy of ampullary neoplasms. *Gastrointest. Endosc.* 1999, 50, 27–33. [CrossRef]
- Koch, K.; Oellig, F.; Oberholzer, K.; Bender, P.; Kunz, P.; Mildenberger, P.; Hake, U.; Kreiter, K.F.; Thelen, M. Assessment of right ventricular function by 16-detector-row ct: Comparison with magnetic resonance imaging. *Eur. Radiol.* 2005, 15, 312–347. [CrossRef]
- 29. Trefethen, L.N. Spectral Methods in MATLAB; Society for Industrial and Applied Mathematics: Philadelphia, PA, USA, 2000.
- 30. Ecabert, O.; Peters, J.; Weese, J. Modeling shape variability for full heart segmentation in cardiac computed-tomography images. *Proc. SPIE Int. Soc. Opt. Eng.* **2006**, *6144*, 1199–1210.
- Wenqiao, T. Development of a fish heterogeneous phantom for estimation of radiation dose rates. *China Nucl. Sci. Technol. Rep.* 1999, 1, 551–569.
- Jian, S.; Wen, Y.; Zhi, Z.; Hao, M.; Chen, L.; Cheng, J. Monte carlo calculation of artificial radionuclide radiation dose rates for marine species in the western pacific. *Radiat. Prot. Dosim.* 2013, 158, 479–486.
- 33. Sefl, M. Geant4 simulation toolkit. Nucl. Instrum. Methods Phys. Res. 2012, 506, 250–303.
- 34. Jianguo, L. A Manual of Radioecology Transfer Parameters; Atomic Energy Press: Beijing, China, 2006.
- 35. Barendsen, G.W. Dose fractionation, dose rate and iso-effect relationships for normal tissue responses. *Int. J. Radiat. Oncol.* **1982**, *8*, 1981–1997. [CrossRef]
- 36. IAEA. Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards; International Atomic Energy Agency: Vienna, Austria, 1992.
- Xiaoping, B. Study of ERICA Code Application in Radiological Impact Assessment of Terres- trial Biota Near Nuclear Power Plant. *Radiat. Prot. Bull.* 2012, 3, 4–9.
- Groen, R.S. Health effects due to radiation from the chernobyl accident. annex d of unscear 2008: Sources and effects of ionizing radiation. Volume 2: Effects. Arch. Neurol. 2011, 52, 373–378.