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A review of edible mushroom radioactivity

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Abstract

The review deals mainly with the situation in Europe where wild-growing mushrooms are widely consumed as a delicacy and some species have been found to be extensively contaminated by radioactive fallout from the Chernobyl disaster in 1986. The natural isotope ^{40}K usually causes activities of 0.8–1.5 kBq kg^{-1} dry matter. Activities of ^{137}Cs, from nuclear weapons testing, below 1 kBq kg^{-1} dry matter, were commonly reported until 1985. The situation changed dramatically after the Chernobyl accident and activities up to tens of kBq kg^{-1} dry matter of ^{137}Cs and to a lesser extent of ^{134}Cs were observed in the following years in some edible species. Among the heavily accumulating species belong *Xerocomus* (*Boletus*) *badius*, *Xerocomus chrysenteron*, *Suillus variegatus*, *Rozites caperata* and *Hydnum repandum*. Activity concentrations have been affected by several environmental factors, such as rate of soil contamination with fallout, the horizon from which mycelium takes nutrients, soil moisture and time from the disaster. Wild mushroom consumption contributed up to 0.2 mSv to the effective dose in individuals consuming about 10 kg (fresh weight) of heavily contaminated species per year. The radioactivity of cultivated mushrooms is negligible. Contamination can be considerably decreased by soaking or cooking of dried or frozen mushroom slices. Animals, such as deer, eating mushrooms, have elevated levels of radionuclides in their tissues. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Wild-grown edible mushrooms; Cultivated mushrooms; Radioactivity; Radiocaesium; Chernobyl disaster

1. Introduction

High radioactivity levels of some wild-growing mushroom species (higher fungi, macrofungi) were observed in the 1960s (Grüter, 1964). The accident of the Chernobyl atomic power station in 1986, and the following contamination of most of Europe with radioactive fallout, initiated extensive research of the environment including mushrooms. Tens of original papers were published on radioactivity, mainly of edible fungi. However, no commonly available review from the hygienic point of view was published on the topic. Consumption of wild-growing mushrooms as a delicacy has been high in many countries, mainly in central and east Europe. For instance, as many as 72% of families collect mushrooms at a yearly medium level 7 kg per household in the Czech Republic (Šišák, 1996). In some individuals, the consumption exceeds 10 kg per year.

Mycologic terms used in this review are given in Fig. 1, taken from our previous review dealing with trace element levels in edible mushrooms (Kalač & Svoboda, 2000). Data on radioactivity levels are usually given per dry matter (DM) content in most papers. For unification, the commonly accepted content of 10% of dry matter in mushroom fruiting bodies was used for calculation in this review, for several data given as fresh weight. The review deals mainly with European mushroom species.

2. Radioactivity units and legislation

One Bq (becquerel) has been the unit for the activity of a radioactive source in which one atom decays per second on average. Activity concentration, that is activity per dry matter unit, is used in this review. The usual statutory limit for foods has been 600 Bq per kg of fresh weight, i.e. 6 kBq per kg of dry matter for mushrooms. However, in response to the Chernobyl disaster, the European Communities published Council Regulation (CEC, 1987) defining values for the maximum permitted levels of foodstuff radioactive contamination. The regulation was established with a view to responding to

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accidents of a similar magnitude to the Chernobyl disaster. Under this regulation, the maximum permitted level of ^{137}Cs for foodstuffs such as mushrooms, was 1.25 kBq kg^{-1} fresh weight (i.e. 12.5 kBq kg^{-1} DM for mushrooms). A similar limit of 1.0 kBq kg^{-1} fresh weight (i.e. 10 kBq kg^{-1} DM for mushrooms) was recommended by the International Atomic Energy Agency (IAEA, 1994).

A possible risk of radioactivity for human health is expressed by the effective dose (E) given in mSv (millisievert) per year. The acceptable yearly burden for an adult, of the public, recommended by the International Commission for Radiation Protection has been 5 mSv. A contribution to the yearly effective dose to an adult from mushroom consumption may be calculated as follows (ICRP, 1996):

$$E = Y \times Z \times d_{\mathrm{k}},$$

where Y = annual intake of mushrooms (kg DM per person), Z = activity concentration (Bq kg^{-} DM), d_{k} = dose coefficient (conversion factor) defined as the dose received by an adult per unit intake of radioactivity. Their values are 1.3×10^{-8}, 1.9×10^{-8} and 6.2×10^{-9} Sv Bq^{-1} for ^{137}Cs, ^{134}Cs and ^{40}K, respectively. During an explosive fission reaction many radionuclides are produced, among them ^{137}Cs and ^{90}Sr with long half-lives 30.17 and 28.8 years, respectively. Another radionuclide important in mushroom contamination, ^{134}Cs (half-life 2.06 years) has been produced in reactors during long-term fission.

3. Natural radionuclides in mushrooms

As observed by Seeger (1978) in a survey of 410 wild-growing species, mushrooms contain between 1.5 and 117 g of potassium per kg of dry matter. Thus, potassium levels in many mushroom species are considerably higher than those in foods of plant origin. Potassium concentrations within the individual parts of a fruiting body decrease in the following order: cap > stipe > gills or tubes in spores-forming part > spores. The concentration factor (fruiting body/substrate) ranged from 20 to 40. The radionuclide ^{40}K is present in the mixture of potassium isotopes at the constant level of 1.17×10^{-2}%.

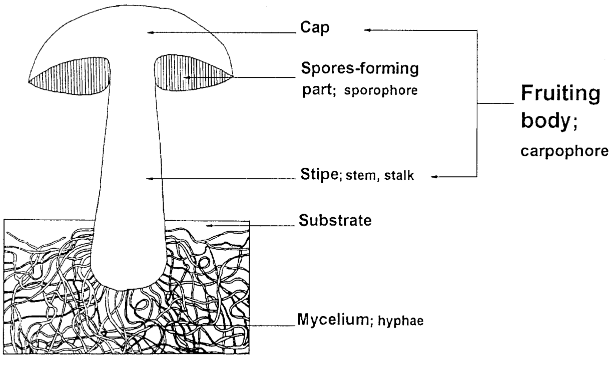

Fig. 1. A sketch of mushroom and used mycologic terms. Fructification is formation of fruiting body.

From Table 1, it can be concluded that usual ^{40}K activity concentrations are between 0.8 and 1.5 kBq kg^{-1} DM for both wild-growing and cultivated species. These levels are higher than those in other foodstuffs. Transfer factors for ^{40}K from growing substrate to fruiting body ranged between 1.5 and 22.7, with values exceeding 10 for *Xerocomus badius*, *Lycoperdon perlatum* and *Amanita rubescens* (Eckl, Hofmann, & Türk, 1986). Comparable values of 7.2, 1.8 and 1.6 were observed for transfer factors from sawdust, used as a growing substrate for fruiting bodies of cultivated *Flammulina velutipes*, *Lentinula edodes* and *Ganoderma lucidum*, respectively (Wang, Wang, Lai, & Lin, 1998).

Data on other naturally occurring radionuclides in mushrooms are very limited. Eckl et al. (1986) reported levels of ^{226}Ra and ^{210}Pb below detection limits in tested edible species. Kirchner and Daillant (1998) found activity concentrations in mushrooms collected in France during the period 1991–1997 up to 36.5 with a mean level of 12 Bq kg^{-1} DM for ^{210}Pb, and often lower by one order of magnitude for ^{226}Ra. Nevertheless, a conversion factor of 6.9×10^{-7} Sv Bq^{-1} was established for ^{210}Pb (CEU, 1996), which is about 50 times higher than the value given above for ^{137}Cs. Thus, ^{210}Pb in mushrooms can contribute to their total effective dose.

4. Artificial radionuclides in mushrooms until 1985

Several radionuclides were discharged into the global environment through nuclear weapons testing until 1963. The total release of the most important radionuclide, ^{137}Cs, was estimated as 9.6×10^{17} Bq (UNSCEAR, 1982).

Most mushroom species have limited ability to accumulate non-radioactive caesium. Seeger and Schweinshaut (1981) found an average level of 7 mg kg^{-1} DM with exceptionally high concentrations within the family Cortinariaceae. The observed concentration factors of the non-radioactive caesium for mushrooms are not significantly different from those for vascular plants. However, in the case of radiocaesium from the fallout, the observed values were at least one order of magnitude higher. The different behaviour of the natural and radioactive caesium may originate from their disequilibrium in the ecosystem (Horyna & Řanda, 1988) and their different availability.

The ability of mushrooms to accumulate ^{137}Cs from fallout was first reported by Grüter (1964). Data on radioactivity of central European species until 1985 are given in Table 2. As can be seen, ^{137}Cs activities below 1 kBq kg^{-1} DM were usual. Mushrooms do not accumulate ^{90}Sr or radioisotopes of plutonium at toxicologically significant levels (Mascanzoni, 1992; Mietelski, LaRosa, & Ghods, 1993).

5. Mushroom radioactivity after the Chernobyl accident

The disaster of the Chernobyl power station on 26 April 1986 released into the environment about 3.8×10^{16} Bq from ^{137}Cs decay (UNSCEAR, 1988). The ratio ^{137}Cs to ^{134}Cs was approximately 2:1. The radioactive contamination of an area was affected not only by distance from Chernobyl but also precipitations from radioactive clouds. Thus, fallout levels could be very different in relatively adjacent sites.

Data on radiocaesium levels in widely consumed mushroom species are given in Table 3. Separately, in Table 4, there are data for *X. (Boletus) badius*, the species massively consumed in many countries of central and east Europe. Activity concentrations of ^{137}Cs and ^{134}Cs are affected by several factors — mushroom species, contamination of soil, time from the disaster, soil horizon from which a species takes nutrients, and moisture.

A list of common species by their ability to accumulate radiocaesium is given in Table 5. However, this distribution cannot be considered precise, as literature data are not unambiguous. *Paxillus involutus* has often been reported among the accumulating species. However, it should not be consumed due to its adverse effects in some people.

Wide differences exist within a species. A unique study was done in Poland with 278 samples of *X. badius* collected systematically, to cover the whole country area, in 1991. Maps of ^{137}Cs, ^{134}Cs and ^{40}K levels in this species were prepared. The most frequent activities were 2–10 and 0.2–0.6 kBq kg^{-1} DM for ^{137}Cs and ^{134}Cs, respectively. The maximum activities, 157 and 16.3 kBq kg^{-1} DM, were observed for those radionuclides (Mietelski et al., 1994).

Radiocaesium migrates vertically in soils only slowly and most of the radionuclides have therefore been available from top organic layers (Pietrzak-Flis, Radwan,

Table 1
Activity concentrations of ^{40}K (kBq kg^{-1} DM) in mushrooms

Species	Activity	Year	Country	References
10 Species	0.45–3.52	1984–1988	Poland	(Bem, Lasota, Kuśmierek, & Witusik, 1990)
About 100 samples	1–2	1986–1989	Italy	(Borio et al., 1991)
Xerocomus badius	1.29	1987	Austria	(Heinrich, Müller, Oswald, & Gries, 1989)
Boletus edulis	1.04			
Suillus luteus	1.22			
Rozites caperata	0.96			
X. badius + *X. subtomentosus*	1.52	1989	Poland	(Kubik, Bem, Kuśmierek, Dzieciol, & Michalczuk, 1991)
X. badius (*n* = 278)	1.3 (0.8–1.6)	1991	Poland	(Mietelski, Jasińska, Kubica, Kozak, & Macharski, 1994)
22 Species	1.29 (Mean)	1989–1990	Hungary	(Vaszari, Toth, & Tarjan, 1992)
X. badius	0.55–1.27	1992	Ireland	(Rafferty, Dowding, & Dawson, 1999)
B. edulis	0.65			
Suillus variegates	0.82			
Suillus granulatus	1.16			
25 Species including not edible	1.15 (Median)	1989	Japan	(Muramatsu, Yoshida, & Sumiya, 1991)
65 Species including not edible	1.10 (Median)	1990	Japan	(Yoshida, Muramatsu, & Ogawa, 1994)
16 Cultivated species	0.05–1.23	1994	Taiwan	(Wang et al., 1998)

Table 2
Activity concentrations of ^{137}Cs (kBq kg^{-1} DM) in mushrooms until 1985[a]

Species	Activity	Year	Country	References
Xerocomus badius	11.3 (maximum)	1966	Germany	(Grüter, 1971)
12 Species	ND–0.28	1981–1983	Austria	(Eckl et al., 1986)
15 Species	0.01–0.75	1984	Austria	(Heinrich et al., 1989)
X. badius (9)	0.24–2.44	1972–1985	Czech Republic	(Řanda, Benada, Singert, & Horyna, 1988)
Xerocomus chrysenteron (6)	0.03–0.97	1970–1985		
Agaricus arvensis (3)	0.1–0.32	1985		
Amanita rubescens (5)	0.01–0.34	1970–1984		
9 Species	0.04–0.47	1984, 1985	Poland	(Bem et al., 1990)

[a] ND, below detection limit; number in bracket, number of samples.

Rosiak, & Wirth, 1996). The high ^{137}Cs activity in the top layer is probably also due to subsequent supply of the radionuclide through dropped needles and leaching from needles and bark. Mushrooms collected in coniferous forests have higher levels of radioactivity than those from deciduous forests (Heinrich, 1992). Species whose mycelium is growing within top layers thus commonly accumulate radiocaesium. Maximum levels of mushroom radiactivity were therefore observed not in 1986, but in 1987, and mainly, in 1988.

Mushrooms growing under conditions of increased soil moisture accumulate significantly more radionuclides due to their increased mobility. These differences can reach one order of magnitude for sites with equal levels of contamination (Tsvetnova & Shcheglov, 1994).

Radiocaesium is distributed unevenly within the fruiting bodies in the order gills > flesh of caps > stipes (Heinrich, 1993). Interesting information on high accumulation of ^{137}Cs in norbadion A, the brown pigment of *X. badius* cap skin (epicutis) was reported by Aumann, Clooth, Steffan, and Steglich (1989). However, only 11 and 12% of the total levels of radiocaesium in two fruiting bodies of *X. badius* were observed in skin, in proportion to its weight (Neukom & Gisler, 1991).

In Japan, where the radioactive fallout from the Chernobyl disaster was low, mean ^{137}Cs activity of mushrooms was 2.6 ± 2.4 kBq kg^{-1} DM in 1989 and 1990. However, in some species, the levels surpassed the Japanese interim limit for foods of 370 Bq kg^{-1} fresh

Table 3
Activity concentrations of radiocaesium (kBq kg^{-1} DM) in mushrooms following the Chernobyl disaster

Species	Number of samples	^{137}Cs	^{134}Cs	Year	Country	References
Boletus edulis	9	ND–31.7		1988–1991	Ukraine	(Smith, Taylor, & Sharma, 1993)
B. edulis	6	0.07–1.15		1986	Czech Republic	(Řanda et al., 1988)
Xerocomus chrysenteron	17	0.3–24.0		1986, 1987		
Leccinum scabrum	5	0.06–33.3		1986, 1987		
X. chrysenteron	–	1.2–25.2		1987–1993	Czech Republic	(Švadlenková, Konečný, & Smutný, 1996)
5 Species	8	0.2–25.2	0.11–10.3	1986	Austria	(Teherani, 1987)
Rozites caperata	1	85.5	25.2	1987	Austria	(Heinrich et al., 1989)
Different	156	0.06–10.3	0.05–2.15	1987,1988	West Germany	(Rückert, Diehl, & Heilgeist, 1990)
B. edulis	19	1.39		1986	Sweden	(Mascanzoni, 1992)
L. scabrum	9	1.73				
Cantharellus cibarius	151	6.14				
Cantharellus tubaeformis	27	10.1				
B. edulis	9	0.1–0.5	0.02–0.08	1986	Italy	(Battiston, Degetto, Gerbasi, & Sbrignadelo, 1989)
Cantharellus lutescens	7	5.0–27.6	1.9–11.6			
Armillariella mellea	4	0.35–1.5	0.11–0.53			
Rozites caperata	3	2.5–18.8	0.23–2.1	1989, 1991	Croatia	(Franić, Senčar, & Bauman, 1992)
Suillus granulatus	10	0.25–1.15	ND–0.015	1990	Japan	(Yoshida et al., 1994)
Armillariella mellea	4	ND–0.14	ND			
B. edulis	3	0.11–0.56		1988–1991	Ontario, Canada	(Smith et al., 1993)

Table 4
Activity concentrations of radiocaesium (kBq kg^{-1} DM) in *Xerocomus badius* following the Chernobyl disaster

Samples (*n*)	^{137}Cs	^{134}Cs	Year	Country	References
1	1.5–8.8		1986–1988	Poland	(Bem et al., 1990)
278	2–10	0.2–0.6	1991	Poland	(Mietelski et al., 1994)
2	15.5		1989	Poland	(Falandysz & Caboń, 1992)
4	3.0–10.7		1987	Czech Republic	(Řanda et al., 1988)
1	42.3	22.9	1987	Czech Republic	(Vobecký & Těthal, 1993)
–	2.0–116		1988–1993	Czech Republic	(Švadlenková et al., 1996)
1	38.5	15.5	1986	Austria	(Teherani, 1987)
1	37.4	11.8	1987	Austria	(Heinrich et al., 1989)
10	0.42–3.2	0.08–0.84	1986–1988	West Germany	(Rückert et al., 1990)
9	13.2–43.6		1987–1991	Bavaria, Germany	(Kammerer, Hiersche, & Wirth, 1994)
3	0.02–1.14	0.01–0.04	1992,1996	France	(Kirchner & Daillant, 1998)
4	1.1–6.2		1992	Ireland	(Rafferty et al., 1999)
5	0.8–9.0	0.25–0.75	1993	Italy	(Saullo, Mones, Magnoni, & Tofani, 1996)

weight (Sugiyama, Shibata, Isomura, & Iwashima, 1994). Activities of ^{137}Cs, in species commonly consumed in Japan, such as *F. velutipes, Pleurotus ostreatus* and *Pholiota nameko*, were below 0.05 kBq kg^{-1} DM in 1989 (Muramatsu, Yoshida, & Sumiya, 1991).

Levels of other Chernobyl radionuclides were of low significance. Teherani (1987) found, in Austrian mushrooms collected in 1986, activity of ^{103}Ru to be 0.04–1.48 kBq kg^{-1} DM with maximum level in *Macrolepiota procera*. Negligible levels up to 0.11 kBq kg^{-1} DM of ^{110m}Ag were determined in several species in Austria in 1987 (Heinrich, Müller, Oswald, & Gries, 1989) and in West Germany in 1986–1987 (Rückert, Diehl, & Heilgeist, 1990).

It is necessary to estimate the dynamics of changes in mushroom radioactivity in the future. Different mushroom species have their mycelia in different soil horizons. Since the radiocaesium activity in these horizons changes with time, the activities in different mushroom species are also expected to behave differently over time. There were identified species with decreasing (i.e. *X. badius*), constant (i.e. *Hydnum repandum* or *Macrolepiota rhacodes*) or increasing (i.e. *Russula cyanoxantha*) contamination. In the future, the mean radiocaesium activity will decrease, giving ecological half-lives between 3 and 8 years for all mushroom species (Rühm, Steiner, Kammerer, Hiersche, & Wirth, 1998). Current knowledge of ^{137}Cs transfer to mushroom fruiting bodies, and the consequences for modelling environmental transfer, were reviewed by Gilett and Crout (2000).

Data on European mushroom radioactivity after 1995 are limited. It is not easy to calculate a contribution of wild-growing mushrooms intake to the effective dose because of limited reliable information on their total consumption, especially differently accumulating species.

Consumption of wild-growing mushrooms with a mean activity level 17 kBq kg^{-1} DM accounted, in the mid 1990s for about 20–40% of ingested radiocaesium and contributed below 0.5 mSv per year in a rural Russian population about 200 km from the Chernobyl power station (Skuterud, Travnikova, Balonov, Strand, & Howard, 1997). Also, in former Czechoslovakia, with mean yearly intake 1.55 kBq from mushrooms in 1988, this item became the most significant source of internal contamination (Horyna, 1991). The contribution to the effective dose for a person, consuming 10 kg (fresh weight) of *X. badius* and *X. chrysenteron* with high mean levels 10 and 2.2 kBq kg^{-1} DM of ^{137}Cs and ^{134}Cs, respectively, was estimated to about 0.2 mSv per year, which was about 20% of the natural background burden in Czechoslovakia (Klán, Řanda, Benada, & Horyna, 1988). However, in most of Europe, the contribution expressed as a percentage of the natural body burden has been low and should be taken into consideration in individuals consuming extremely high levels (tens of kg of fresh weight per year) of wild-growing accumulating species.

Table 5
Selected mushroom species with different rates of radiocaesium accumulation

High	Medium	Low
Xerocomus badius	*Leccinum scabrum*	*Boletus edulis*
Xerocomus chrysenteron	*Leccinum aurantiacum*	*Cantharellus cibarius*
Suillus variegatus	*Agaricus silvaticus*	*Macrolepiota procera*
Cantharellus tubaeformis		*Armillariella mellea*
Cantharellus lutescens		*Amanita rubescens*
Rozites caperata		*Laccaria laccata*
Hydnum repandum		
Laccaria amethystina		*Lycoperdon perlatum*
Russula cyanoxantha		*Calocybe gambosa*
		Pleurotus ostreatus

The annual effective dose of ^{137}Cs, due to the consumption of wild-growing mushrooms in Mexico, was estimated to be below 1 Sv y^{-1}, which represents 37–66% of the total dietary intake of the radionuclide (Gaso, Segovia, Cervantes, Herrera, & Perez-Silva, 2000; Gaso, Segovia, Morton, Cervantes, Godinez, Pena, & Acosta, 2000).

6. Radioactivity of cultivated mushrooms

Activity of ^{137}Cs in 16 cultivated species was negligible (up to 0.007 kBq kg^{-1} DM). The transfer factors from sawdust as growing substrate, for fruiting bodies of *F. velutipes, G. lucidum* and *L. edodes* were ~10, 10.2 and <3.8, respectively (Wang et al., 1998). A similar transfer factor, about 14, for *F. velutipes* was reported by Ban-nai, Yoshida, and Muramatsu (1994).

7. Decrease of mushroom radioactivity by soaking and cooking

The extraction of radiocaesium from *X. badius* intact fruiting bodies into soaking water or table salt solution is low due to the mushrooms lipophilic gel-like surface layer. On the other hand, an almost complete decontamination was observed in dried or frozen mushroom slices with destroyed cell tissues (Neukom & Gisler, 1991).

During cooking of *X. badius* and *X. chrysenteron* slices, 80 and 87% of ^{137}Cs was released into cooking water after 5 and 20 min, respectively (Klán et al., 1988). Similarly, radiocaesium levels decreased by 36–63% during cooking of *Stropharia rugusoannulata* in 2% table salt solution for 15 min (Steger, Burger, Ziegler, &

Wallnöfer, 1987). Blanching and cooking of four mushroom species cut into small parts decreased radiocaesium levels by 58–82% (Skibniewska & Smoczyński, 1999). These decontamination treatments remove a lot of compounds affecting attractive smell.

8. Accumulation of radiocaesium in tissues of animals eating mushrooms

Levels of radiocaesium increase in tissues of animals eating mushrooms and lichens. This was observed for both wild ruminants, such as roe deer (*Capreolus capreolus*) and reindeers (*Rangifer tarandus*; Karlén, Johanson, & Bergström, 1991; Strandberg & Knudsen, 1994), and in grazing domestic goats and sheep (Hove, Pedersen, Garmo, Hansen, & Staaland, 1990) as a characteristic mainly of Scandinavia, which has a very high density of mushrooms. Contamination of game meat with ^{137}Cs was higher in red deer (*Cervus elaphus*) than in roe deer and wild boar (*Sus scrofa*) in the Czech Republic. The levels were below 100 Bq kg^{-1} meat and have decreased since 1986 (Švadlenková, Konečný, & Smutný, 1996).

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