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The influence of ionizing radiation on spore germination and emergent hyphal growth response reactions of microfungi

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Abstract: The accident at the Chernobyl Atomic Energy Station resulted in radiation contamination of large tracts of land and particularly the reactor building itself. Sustained exposure of microfungi to radiation appears to have resulted in formerly unknown adaptive features, such as directed growth of fungi to sources of ionizing radiation. We evaluate here spore germination and subsequent emergent hyphal growth of microfungi in the presence of pure γ or mixed β and γ radiation of fungi isolated from a range of long term background radiation levels. Conidiospore suspensions were exposed to collimated beams of radiation and percent spore germination and length of emergent hyphae were measured. All fungal species isolated from background radiation showed inhibition or no response in germination when irradiated. Isolates from sites with elevated radiation showed a stimulation in spore germination (69% mixed radiation and 46% for γ irradiation). Most isolates from low background radiation sites showed a significant reduced or no response to exposure to either source of radiation, whereas the stimulatory effect of experimental exposure to radiation appeared to increase in magnitude as prior exposure to radiation increased. We propose that the enhanced spore germination and hyphal growth seen in the exposure trials is induced by prior long term exposure to radiation and these factors could be important in controlling the decomposition of radionuclide-bearing resources in the environment.

Key words: hyphal growth, ionizing radiation, microfungi, spore germination

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INTRODUCTION

The accident in the 4th block reactor at Chernobyl Atomic Energy station (ChAES) has resulted in radiation contamination of millions of acres, but most fallout is in the remnants of the reactor room and surrounding areas. At the time of the ChAES accident ejected gases contained about 5% radioactivity. Other fuel remains in the remnants of the reactor room have an activity of 2.4×10^{20} Bq. Of these the activity of long-lived isotopes contained approximately 6×10^{17}Bq (6×10^7 Ci) (Paton et al 2003, Zheltonozhsky et al 2001). Thus large areas have been subjected to the long term influence of a chronic irradiation, although of differing intensity.

Sustained radiation exposure to biota as a whole and to mycobiota in particular has generated a number of formerly unknown adaptive features. One of these is radiotropism; directed growth of microfungi to sources of ionizing radiation (Zhdanova et al 1991, Tugay et al 2003, Zhdanova et al 2004) has special significance. They showed that fungi isolated from radioactive soil possessed radiotropism and that growth could be stimulated by repeated irradiation. Radiostimulation (radiating hormesis) also was explored. Such effects are known in the literature for plants and animals (Alshits 1981; Zhuravskaya 1995; Calabrese 1999, 2000).

Microfungi (anamorphs, producing condiospores) represent an extensive group of organisms in soil that perform an essential role of aiding the transformation of radioactive particles with high specific activity to a soluble form. These soluble elements are capable of leaching, sorbing or becoming accumulated into food webs (Haselwandter 1978, Zhdanova 2003).

The reaction of fungi to pure sources of radiation, decoupled from the carbon base supporting them, has been explored (Zhdanova et al 2004). In the current work we have evaluated the radiostimulation response of fungi that were isolated from sites that have experienced different levels of radioactivity in the 10–17 y after the nuclear accident, when grown close to sources of pure γ or mixed β and γ radiation. To our knowledge no other studies report positive growth responses of fungi to ionizing radiation.

MATERIALS AND METHODS

Fungal isolation.—Fungi were isolated from variety of locations in Ukraine. Some of these locations were

radioactively contaminated (inside the former reactor room and from soil in the 10 km zone around ChAES) . Control strains were isolated from sites with background radiation, remote from Chernobyl. All strains are maintained in the culture collection of the Institute of Microbiology and Virology, Kiev.

Irradiation system.—Research on the influence of sustained radiation on growth was carried out in a model system. Radioactive emissions from selected sources were collimated with a lead irradiation box consisting of a central well, housing the radioactive source, and 1 mm diam holes drilled through 2 cm lead walls in each of the four sides and the lid.

Two types of radiation were used, a source of practically clean gamma radiation (^{121}Sn) and a source of mixed beta and gamma radiation (^{137}Cs → ^{137}Ba). These have different gamma emission energy (27 keV and 662 keV, respectively) and similar total activities measured at the top of collimater (about 2×10^5 Bq), where the target plastic Petri plate or cavity slide was placed over the top port. Activated fungal suspension (about 100 mg), consisting of approximately 4×10^5 spores (about 0.5–1.5% by mass) was exposed to a radiant flux 2×10^5 (particles mm^{-2}) gamma radiation with energy Eγ = 662 keV for (^{137}Cs) and accordingly Eγ = 27 keV for ^{121}Sn. This exposure of the conidial suspension in nutrient medium is equivalent to approximately 5×10^9 Bq kg^{-1} or 20×10^9 Gy/y, equating to about $5\ 5 \times 10^7$ Gy/d. Taking into account weight and size of conidia (2–5 μm) each conidiospore obtained a dose of 40–60 Gy/d.

The spores were exposed to chronic irradiation 5–7 d, after which growth characteristics were determined for each of the strains. The absorbed dose of gamma radiation consisted of 100–150 Gy of ^{137}Cs and was lower than that from ^{121}Sn (200–400) Gy. At the same time the ^{137}Cs source provided an absorbed dose from electrons (beta radiation) of 300–500 Gy. Control samples were not exposed to irradiation.

Conidial germination and hyphal length measures.—We investigated two response reactions, percent of conidia germination and length of the emergent hyphae. Such an investigation let us estimate a comparative degree of response depending on the influence of each of the listed factors.

At the end of each experiment the condiospores and their emergent hyphae were photographed with a light microscope with an attached Nikon Coolpix 3500 digital camera. Image processing to determine the percent of spore germination and lengths of emergent hyphae was carried out with Scion image and Excel software packages. Percent spore germination was determined as a single value from the spore population, so statistical comparisons between radiation treatments within a species was not possible.

Statistical analyses.—Analysis of variance of emergent hyphal length between radiation treatments within a species was carried out with the GLM procedure of SAS (1989–1996) because numbers of hyphae measured were not equal between treatments. Means separation between treatments was conducted with the Tukey significant difference post-hoc test.

RESULTS

We previously had carried out research to detect the presence radiotropic reaction from frequently isolated fungal strains from localities of high radioactive exposure and control strains, isolated from clean localities. Radioactive conditions (40–500 mR h^{-1}) of the site of isolation and their radiotropic responses when grown in culture in the presence of collimated radiation are provided (TABLE I). Of fungal species isolated from radioactively contaminated areas, most (10 out of 13) showed positive radiotropism and all fungi isolated from clean areas (control) did not show this property. Of strains that showed positive radiotropism, some at the same time showed stimulation of growth of emerging hyphae. To characterize the degree and frequency of this process, we measured hyphae length. The influence of two types of sources of radiation—source gamma radiation, ^{121}Sn, and mixed beta and gamma radiation, ^{137}Cs—on the percent of conidia germination and length of emerging hyphae was investigated. The fungi are represented by three genera and eight species, which belong to two families, Dematiaceae and Moniliaceae.

Conidial germination.—The influence of two sources of radiation, ^{121}Sn and ^{137}Cs, on the percent of conidia germination of 17 isolates of four genera of microfungi is presented (TABLE II). A number of general conclusions were drawn. All species isolated from clean sites showed either an inhibition of conidia germination or no difference in germination under exposure to one of the radiation sources. *Aspergillus versicolor* 432, *Cladosporium cladosporioides* 4061 and *C. cladosporioides* 396 all showed reduced conidial germination in the presence of ^{137}Cs. Other isolates from clean sites showed no change in conidial germination in the presence of radiation compared with control. We investigated 15 strains from locations with different levels of radioactive pollution. Of these nine fungal strains (60%) under ^{137}Cs irradiation and six strains (40%) under ^{121}Sn irradiation showed an increase in germination in the presence of ionizing radiation. Of these, five strains (48%) showed conidia germination under exposure to mixed (gamma + beta) radiation and five (48%) showed activation under influence just one type from used sources of radiation. Only *Hormoconis resinae* 77, isolated from the damaged reactor room, with radioactivity at 30 000 mR h^{-1}, showed

TABLE I. Fungal species and isolate used in this study together with the radioactive conditions at the location of isolation and their radiotropic responses. Abbreviations for isolates used elsewhere in this paper are given in parentheses in column 1

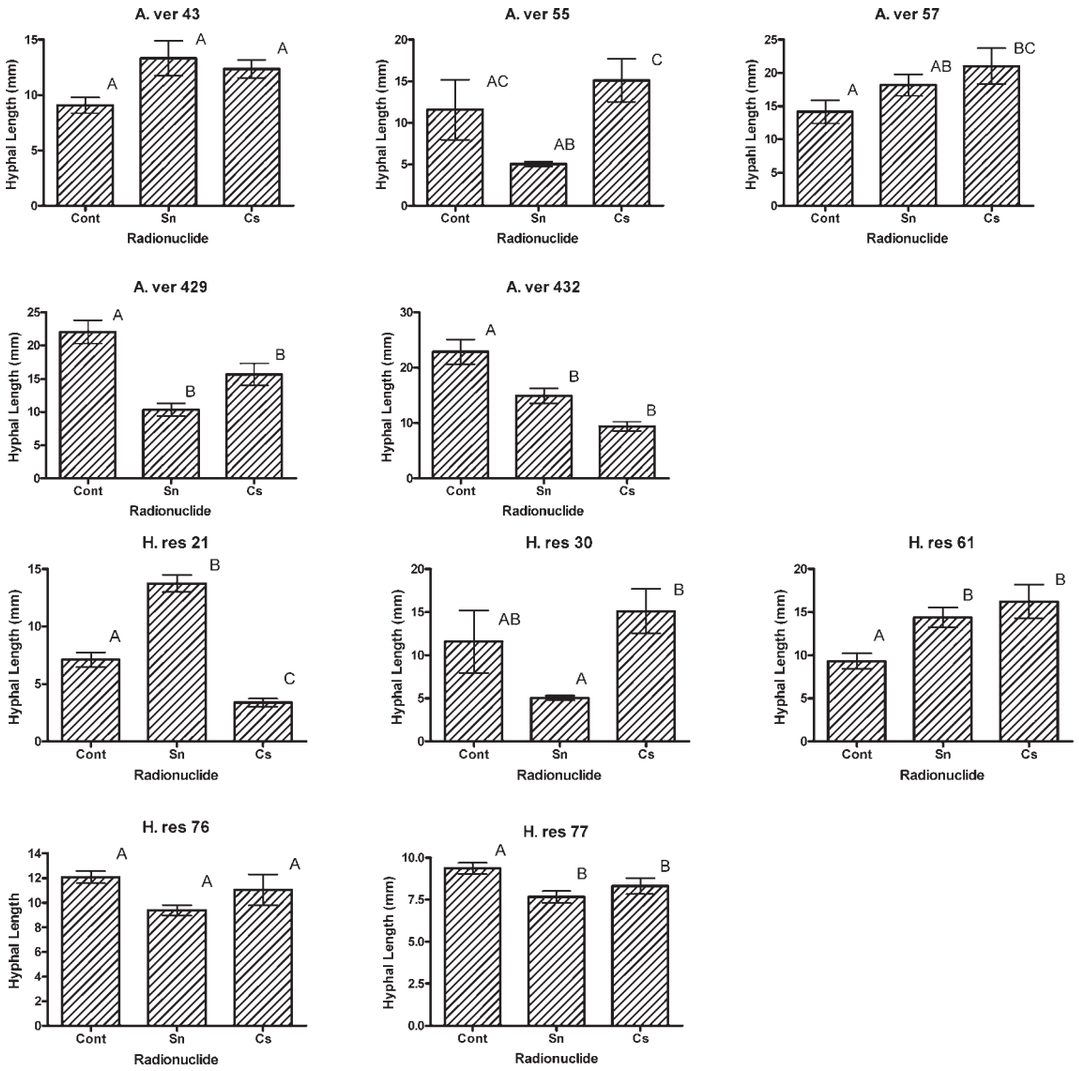
Species	Radioactivity of substrate time	Tropism
Penicillium steckii (Zalessky) 2 (Pst2)	6×10^4 Bq	positive
Aspergillus versicolor ((Vuill.) Tirb.) 432 (A ver 432)	Control	No tropism
Aspergillus versicolor ((Vuill.) Tirb.) 429 (Aver 429)	Control	No tropism
Aspergillus versicolor ((Vuill.) Tirb.) 43 (Aver 43)	The 4th block ChAES 55 mR h^{-1}	positive
Aspergillus versicolor ((Vuill.) Tirb.) 55 (A ver 55)	The 4th block ChAES 250 mR h^{-1}	positive
Aspergillus versicolor ((Vuill.) Tirb.) 57 (A ver 57)	The 4th block ChAES 500 mR h^{-1}	positive
Hormoconis resinae (Lindau) *v. Arx & de Vries f. Resinae 30*	The 4th block ChAES 41 mR h^{-1}	positive
Hormoconis resinae (Lindau) *v. Arx & de Vries f. Resinae 21* (H res 21)	The 4th block ChAES 300 mR h^{-1}	positive
Hormoconis resinae (Lindau) *v. Arx & de Vries f. Resinae 61* (H res 61)	The 4th block ChAES 300 mR h^{-1}	positive
Hormoconis resinae (Lindau) *v. Arx & de Vries f. Resinae 76* (H res 76)	The 4th block ChAES 10 000 mR h^{-1}	No tropism
Hormoconis resinae (Lindau) *v. Arx & de Vries f. Resinae 77* (H res 77)	The 4th block ChAES 30 000 mR h^{-1}	No tropism
Penicillium aurantiogriseum (Dierckx) 60 (P aur 60)	The 4th block ChAES 380 mR h^{-1}	positive
Penicillium spinulosum (Svilv.) 87 (P spin 87)	The 4th block ChAES < 200.000 mR h^{-1}	No tropism
Penicillium roseopurpureum (Dierckx) 147 (P ros 147)	Soil of 10-km zone of ChAES $1{,}4 \times 10^6$ Bq kg^{-1}	positive
Cladosporium sphaerospermum (Penz.) 70 (C sph 70)	The 4th block ChAES 300 mR h^{-1}	positive
Cladosporium cladosporioides ((Fresen.) G. A. de Vries) 396 (C cl 396)	Control	No tropism
Cladosporium cladosporioides ((Fresen.) G. A. de Vries) 4061 (C cl 4061)	Control	No tropism

inhibition of conidia germination under exposure to both sources of radiation.

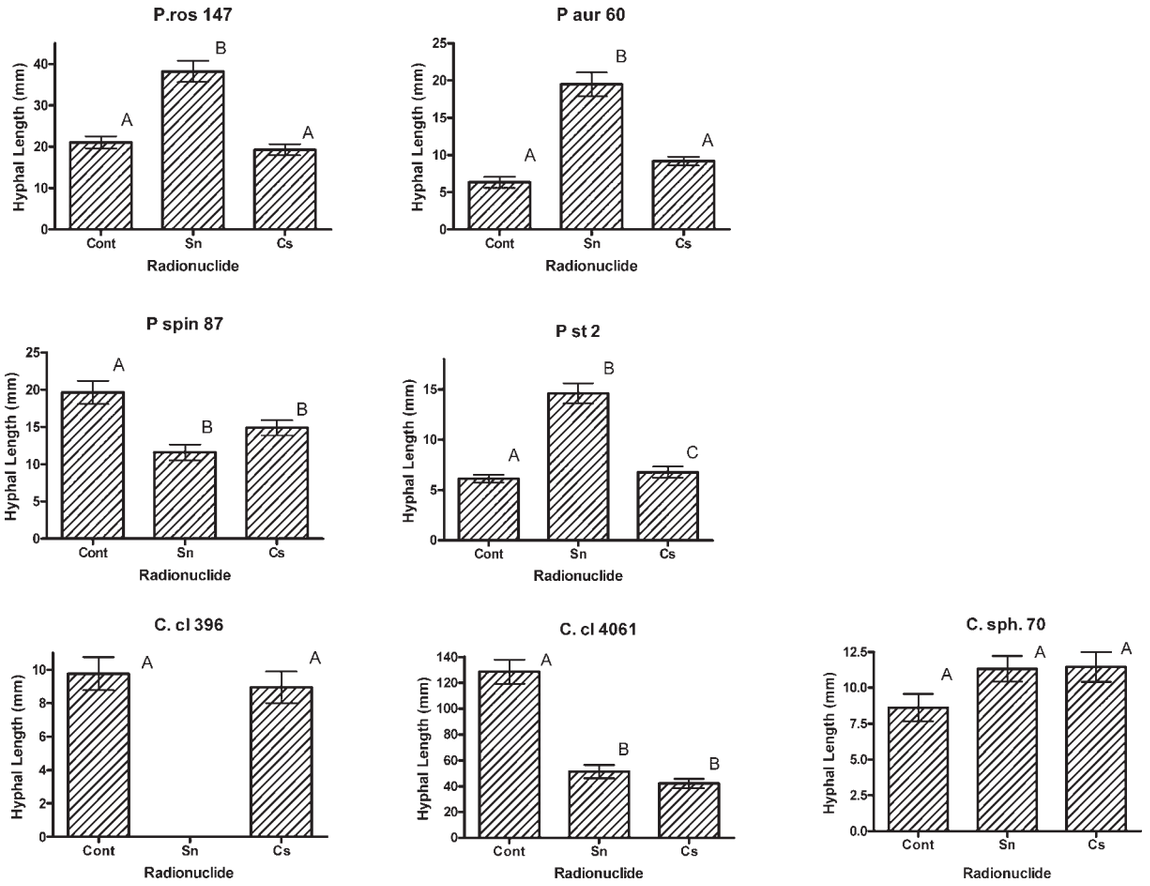
All fungi isolated from clean locations did not show radiostimulation of conidia germination after irradiation. However 92% of strains isolated from contaminated sites showed enhanced conidia germination after exposure to at least of one type of ionizing radiation.

TABLE II. Percent spore germination in control and two radiation stimulated suspensions (see text for details of radiation details)

		Ionizing radiation treatment		
Fungal isolate	Radiotropism	Control	$^{121}Sn - \gamma$	$^{137}Cs - \beta + \gamma$
Pst2	+	88.24	88.24	78.72
Pspin 87	−	38.89	13.11	48.50
P aur 60	+	32.0	57.38	25.74
Pros 147	+	77.08	88.37	84.09
Aver 43	+	39.52	48.21	54.25
Aver 55	+	8.06	2.73	9.44
Aver 57	+	15.27	14.15	17.22
Aver 429	−	20.22	24.11	20.18
Aver 432	−	9.33	8.06	3.61
Ccl 4061	−	28.80	24.2	8.0
Csph 70	+	47.56	62.74	75.0
Hres 21	+	50.67	51.52	82.14
Hres 30	+	33.02	15.04	67.27
Hres 61	+	24.07	51.55	33.33
Hres 76	−	86.7	82.2	89.3
Hres 77	−	70.3	51.62	51.03
Ccl 396	−	28.0	—	14.5



FIGS. 1–4. 1. Comparative mean emergent hyphal lengths (mm) between fungal spores of *Aspergillus versicolor* (see TABLE I for details of isolate location) exposed to no radiation (Cont) and collimated sources of radiation from ^{121}Sn or ^{137}Cs. Histogram bars with different letters indicate statistically different means as calculated by Tukey's significant difference post-hoc test. In general isolates from radioactively contaminated sites (55, 250, 500) show increased hyphal growth in the presence of ionizing radiation. 2. Comparative mean emergent hyphal lengths (mm) between fungal spores of *Hormoconis* species (see TABLE I for details of isolate location) exposed to no radiation (Cont) and collimated sources of radiation from ^{121}Sn or ^{137}Cs. Histogram bars with different letters indicate statistically different means as calculated by Tukey's test. Isolate 77 from the highest level of radiation contamination and showing no radiotropism showed suppression of hyphal growth in the presence of ionizing radiation. Other isolates, although from contaminated soils, showed variable response to the ionizing radiation from the two sources. 3. Comparative mean emergent hyphal lengths (mm) between fungal spores of *Penicillium* species (see TABLE I for details of species and isolate location) exposed to no radiation (Cont) and collimated sources of radiation from ^{121}Sn or ^{137}Cs. Histogram bars with different letters indicate statistically different means as calculated by Tukey's test. All isolates from radioactively contaminated sources (147, 60, 2) showed significantly enhanced hyphal growth in the presence of γ-radiation from Sn, which suppressed growth in isolate 87, isolated from an uncontaminated site. 4. Comparative mean emergent hyphal lengths (mm) between fungal spores of *Cladosporium* species (see TABLE I for details of species and isolate location) exposed to no radiation (control) and collimated sources of radiation from ^{121}Sn or ^{137}Cs. Histogram bars with different letters indicate statistically different means as calculated by Tukey's test. Isolates 396 and 4061 from uncontaminated sites showed a suppression of hyphal growth in response to either one or the other source of ionizing radiation, whereas isolate 300, from a contaminated source, showed enhanced hyphal growth.



FIGS. 1–4. Continued.

It is interesting to note that for all isolates that do not show radiotropism (isolates from clean areas and those from highly radioactive areas) show significantly lower rates of spore germination in the presence of Sn and Cs isotopes. For Sn the germination rate is 72.7 ± 8.98% of the control (nonirradiated) for nonradiotropic isolates and 130.3 ± 17.72% for radiotropic isolates ($t = 2.383$. $P = 0.0319$). For Cs the equivalent values are 67.32 ± 13.20 for nonradiotropic and 115.3 ± 10.71 for radiotropic isolates ($t = 2.838$, $P = 0.0125$). The *t*-tests were performed on the germination value expressed as a percentage of the control.

Hyphal lengths.—Results of the influence of both sources of radiation, ^{121}Sn and ^{137}Cs, on length of emerging hyphae and summary statistical analyses are presented (FIGS. 1–4 and TABLE III respectively). It was shown that three out of four strains isolated from clean localities showed a significant reduction in hyphal length, or no reaction, to the presence of ionizing radiation. Fungal strains, isolated from high radioactively contaminated sites (from10 000 mR h^{-1} up to and exceeding 200 000 mR h^{-1}) (e.g. *H. resinae* 76 and 77 and *P. spinulosum* 87), showed inhibition or no change in mean hyphal length under both sources of radiation or showed positive radiotropism. Fungal strains, isolated from sites with lower levels of radioactivity, showed varied response to ionizing radiation. *Aspergillus versicolor* 57 showed an increase in hyphal length in the presence of Cs, whereas isolates 43 and 55 of this species respectively showed no response or a significant reduction in the presence of Sn. *H. resinae* 21 and 61 showed respectively an increase in growth to Sn and both radionuclides, but isolate 30 showed no response. Both *Penicillium* species isolated from moderate radiation (*P. roseopurpureum* and *P. aurantogrisium*) showed enhanced hyphal growth in the presence of Sn only. *Cladosporium sphaerospermum* 70 showed no change in hyphal length in the presence of ionizing radiation compared to the control.

TABLE III. Summary analysis of variance and means separation of emergent hyphal length of microfungi exposed to radiation from a ^{121}Sn and ^{137}Cs source or no radiation (control, C) treatments (see text for details of radiation treatment and isolate source)

Spp	F	P	C vs. Sn	C vs. Cs	Sn vs. Cs
Pst2	44.83	0.0001	*	*	*
Pspin 87	8.22	0.0004	*	*	NS
P aur 60	38.09	0.0001	*	NS	*
Pros 147	31.31	0.0001	*	NS	*
Aver 43	2.65	0.0729	NS	NS	NS
Aver 55	3.76	0.0259	NS	NS	*
Aver 57	3.07	0.0509	NS	*	NS
Aver 429	11.97	0.0001	*	*	NS
Aver 432	12.96	0.0001	*	*	NS
Ccl 4061	40.98	0.0001	*	*	NS
Csph 70	2.88	0.0610	NS	NS	NS
Hres 21	59.36	0.0001	*	*	*
Hres 30	4.90	0.085	NS	NS	*
Hres 61	5.09	0.0078	*	*	NS
Hres 76	2.09	0.1255	NS	NS	NS
Hres 77	14.18	0.0001	*	*	NS
Ccl 396	0.33	0.566		NS	

Note Ccl 396 compares control and Cs only (Sn not included).

DISCUSSION

We showed that more than 60% of fungal strains isolated from the region around ChAES exhibit positive radiotropism (Zhdanova et al 2004). We concluded that this might have been a derived state resulting from long-term exposure to ionizing radiation. In addition, after repeated irradiation by artificial sources of radiation (^{137}Cs, ^{123}Te, ^{109}Cd, ^{121}Sn), these isolates showed significant growth stimulation in the presence of ionizing radiation, a property we call radiostimulation. Mitosporic fungi, isolated from uncontaminated locations did not exhibit these properties. The processes of radiostimulation and radiation hormesis are known from the literature to occur in plants and animals living with increased background radiation (Alshits et al 1981; Zhuravskaya et al 1995; Tverskoy et al 1997; Calabrese and Baldwin 1999, 2000). In this paper we document radiostimulation of conidiospore germination.

Radiostimulation of conidiospore germination is demonstrated in 10 fungal isolates of six species (TABLE II) and radiostimulation or radiation hormesis are demonstrated in hyphal length increase for five isolates of six species of microfungi (TABLE III) isolated from contaminated sites. We suggest that this is evidence of natural adaptive reactions to radiation in fungi. Radiostimulation of conidial germination was influenced by a type of radiation. More stimulation was afforded by the mixed β and γ radiation from ^{137}Cs than from pure γ radiation from ^{121}Sn.

For both spore germination and hyphal growth, fungi response appears to be related to the history of exposure to radioactivity. In all cases of conidial germination and hyphal growth in fungi isolated from clean areas, we observed either no effect or an inhibitory effect of exposure to either radionuclide. Where fungi had been isolated from sites with high background radiation, there tended to be suppression of spore germination (an exception was *Penicillum spinulosum* 87) and for all in hyphal growth. This suggests that prior radiation exposure could elicit the radiostimulation response in these fungi. Some strains, *Aspergillus versicolor* 55, *Penicillium spinulosum* 87 and *Hormoconis resinae* 76, showed spore germination inhibition under gamma radiation and activation when exposed to a mixed source. Thus it is possible that different physiological mechanisms underlie these response reactions.

The pattern of fungal responses to irradiation is different between spore germination and hyphal length enhancement. The influence of both sources of radiation on hyphal length appears to correlate with radioactivity in the areas from which the strains were isolated. Some degree of correlation between the exhibition of radiotropism by fungal isolates and radiostimulation of their hyphal growth also was observed.

Radiostimulation of emerging hyphae was found only in strains isolated from contaminated areas with radioactivity of 40–500 mR h^{-1}. Fungal strains, isolated from more radioactive sites (10 000–100 000 mR h^{-1}) showed some degree of inhibition of hyphae

growth from ionizing radiation (i.e. *Hormoconis resinae* 76, 77 and *Penicillium spinulosum* 87). No effect or inhibition of hyphae growth was seen in isolates from areas without elevated background radiation.

It is important to note that the doses received by microfungi exhibiting radiostimulation of hyphal growth and conidial germination after gamma irradiation (^{121}Sn) 200–400 Gy and mixed beta and gamma irradiation (^{137}Cs) (100–150) Gy (equivalent to an absorbed dose from electrons of 300–500 Gy) considerably exceeds doses known in the literature for animals and plants (Alshits et al 1981, Zhuravskaya et al 1995, Calabrese et al 2000). These responses testify to the high radioresistence of these strains, which possibly developed under long-term radiation exposure. To corroborate this phenomenon, radiotropism and radiostimulation was absent in fungal species isolated from previously clean areas. These properties of fungi, and their ability to accumulate and absorb radioactive elements (Haselwandter 1978, 1994; Dighton at al 1988, 1996; Zhdanova et al 2003) might be important for the understanding of potential and actual roles of fungi in site remediation.

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