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Mercury in raw mushrooms and in stir-fried in deep oil mushroom meals

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ABSTRACT

Wild-grown mushrooms are known to bioaccumulate significant amounts of mercury. However, there is no data on Hg in cooked mushroom found in stir-fried in deep oil meals, which is a popular way of cooking in Asia. Content, possible intake and distribution of Hg in the morphological parts (caps and stipes) of both uncooked (raw) and cooked (stir-fried in deep oil) fruiting bodies of the *Baorangia bicolor*, *Boletus calopus*, *Boletus flammans*, *Boletus obsclereumbrinus*, *Rubroboletus sinicus*, *Boletus speciosus*, *Rugiboletus extremiorientalis* mushrooms and in unidentified *Xerocomus* sp. were investigated. Mushrooms from the region adjacent to the city of Yuxi in the Yuxi county, Yunnan Province, SW China were foraged in 2017. Stir-fried in deep oil boletus mushrooms are have high culinary value and are about 4 times more calorific than fresh mushrooms. Due to the significant dehydration caused by high-temperature cooking and the limited loss of Hg, fried mushrooms may contain lower concentrations of Hg than fresh mushrooms when calculated on a dry basis, but the value may be higher on a whole (wet) weight basis. The median values of Hg concentration, when expressed on a whole (wet) weight basis, were in the range 0.046 to 0.75 mg kg^{-1} in raw mushrooms and 0.33 to 2.2 mg kg^{-1} in the fried mushrooms. Estimated intake of Hg, resulting from consumption by adults (body weight 60 kg) of 100 g × 1 to 100 g × 7 per week of fried mushrooms, was equivalent to doses in the range from 0.55 to 3.7 μg kg^{-1} body weight (RfD is 0.3 μg kg^{-1} body weight) to 3.8 to 26 μg kg^{-1} body weight (PTWI is 4.0 μg kg^{-1} body weight) respectively.

1. Introduction

Mushrooms are rich in minerals but also contain high levels of some toxic metallic and metalloid elements (Falandysz and Borovička, 2013). Little is known about the fate of metallic and metalloid elements accumulated in mushrooms as a result of culinary processing and their status in mushroom meals (Falandysz et al., 2019; Pankavec et al., 2019). China is the largest producer, consumer and exporter of mushrooms worldwide (CEFA, 2016). 35,966,586.35 t of mushrooms were produced in 2016 including 48,347.20 t of the boletes (46,220.00 t of which were foraged from the Yunnan province). China has about 1100 species of edible fungi and numerous mushroom dishes and recipes, and boletus mushroom *sensu lato* are highly prized (Falandysz et al., 2015a; Kojta et al., 2015; Wang et al., 2014; Wu et al., 2016).

Geochemical anomalies in the regions of SW China mean that mushrooms foraged there are elevated in both essential minerals and also in some toxic metallic and metalloid elements, for example, mercury (Hg) or arsenic (As) (Falandysz et al., 2016, 2017; Komorowicz et al., 2019; Li et al., 2018; Zhang et al., 2015). Therefore, there is a general interest in the content and composition of both nutritional and toxic elements including Hg, in both raw mushrooms, and also in mushroom meals commonly consumed in SW China.

Mushrooms are a kind of land vegetation that accumulates Hg well (Falandysz et al., 2003a, 2007a; Kojta and Falandysz, 2016; Melgar et al., 2009; Rzymski et al., 2016; Tuzen and Soylak, 2005), but the extent to which this occurs depends on the fungal species, i.e. its genetic features determined by the presence of the specific transporter gene and ligands, the physiology, and the degree of Hg contamination in the soil or plant substrate (Crane et al., 2010; Falandysz, 2016, 2017; Gabriel et al., 2016; Krasińska and Falandysz, 2015, 2016; Vogel-Mikuš et al., 2016). Mushrooms collected from a region where there is a geochemical anomaly e.g. due to the presence of a mercuriferous belt, may be

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particularly high in Hg. In a randomly collected sample of boletus mushrooms from the Yunnan province this element was up to 22 mg kg^{-1} dry biomass (db) (Falandysz et al., 2015b, 2016; Wiejak et al., 2016). In Europe, *Boletus aereus* from Spain had Hg of 10 ± 3 mg kg^{-1} db (Ostos et al., 2015). *Boletus edulis* collected from a region with a history of extraction and smelting cinnabar in Idrija (Slovenia) had concentrations of 99 ± 5 mg kg^{-1} db of Hg (Vogel-Mikuš et al., 2016). Specimens of *Lactarius quietus* from the cinnabar mining area in Rudňany (Spis region of Slovakia) had concentrations of 48 ± 120 (max. up to 470) mg kg^{-1} db of Hg (Árvay et al., 2014).

In unpolluted areas (background), mushrooms are less contaminated, but they can still contain more Hg than foods of plant origin there, including leafy vegetables. For example, a weak Hg bio-concentrator, such as the ectomycorrhizal *Amanita muscaria*, collected from several spatially distant background areas in Europe, had Hg with concentrations in the range from 0.24 ± 0.13 to 1.4 ± 0.6 mg kg db^{-1} (caps), while good accumulators, such as the ectomycorrhizal *B. edulis* and saprophytic *Macrolepiota procera*, had Hg in the range from 1.1 ± 1.4 to 7.6 ± 3.1 mg kg^{-1} db and 1.1 ± 1.0 to 8.4 ± 7.4 mg kg^{-1} db respectively (Falandysz et al., 2001, 2007a,b,c). Mercury is found in fungi in a wide range of concentrations, in contrast to the essential metallic elements, which are largely regulated by species and occur in a narrow range, e.g., copper and zinc in caps of *A. muscaria* from 29 to 48 mg kg^{-1} db and 89 to 220 mg kg^{-1} db respectively (Falandysz et al., 2007d, 2018; Lipka and Falandysz, 2017, 2018).

A different but less-studied aspect of the biology of mushrooms is the species-specific ability to absorb, translocate and accumulate Hg is associated with the ligand(s) produced by the fungus (Falandysz and Borovička, 2013). This along with other aspects can also play a role in the fate of Hg and the final content and bioavailability of cooked mushrooms and toxicity of a meal (Falandysz and Drewnowska, 2015, 2017). Mercury is a chalcophile element and sulphur (S) is its main ligand in fungi, although selenium (Se) can also act in this role (Vogel-Mikuš et al., 2016). Many mushroom species are characterized by high S content, e.g. *A. muscaria* has an average of 930 to 2650 mg kg^{-1} db and *B. edulis* from 9080 to 13,780 mg kg^{-1} db, and Hg and S concentrations are correlated in fungi (Nasr and Arp, 2011; Nasr et al., 2012). Recently, sulphate (S^{6+}) and reduced sulphur (S^{2-}) were identified in *B. edulis* (Kavčič et al., 2018). Reduced sulphur (-SH or thiol) is found in larger molecules such as glutathione (GSH), cysteine, methionine and thiol-rich compounds, such as metallothioneins, phytochelatins and enzymes, which in addition to Hg can also bind the chalcophile elements, such as Ag, Cd or Zn. Some mushrooms are rich in both Hg and Se, e.g., *B. edulis* (Falandysz, 2008). Nevertheless, Se and Hg in *B. edulis* or other fungi do not seem to correlate with each other (Falandysz et al., 2003). It was discovered recently that Se and Hg form the HgSe compound in *B. edulis*, in which, about 5% of the Hg pool accumulated by this species is sequestered (Vogel-Mikuš et al., 2016). The HgSe compound occurs in nature as a mineral called Tiemannite, which in practice is insoluble in water (1.0×10^{-59} mol in dm^3). Therefore, Hg bound in HgSe can be considered biologically inaccessible with a mushroom meal.

Methylmercury ($MeHg^+$), which in terms of toxicity is the most important Hg compound in the natural environment, is a rather minor Hg compound in mushrooms (usually up to about 5% of total Hg) (Stijve and Roschnik, 1974). Mercury was detected in *B. edulis* in > 80% in forms bound to -SH in macromolecules, in about 5% as $MeHg^+$ and in approximately 5% as HgS and HgSe, respectively (Vogel-Mikuš et al., 2016).

Cooking (blanching and marinating) usually decreases the content of metallic and metalloid elements, but also depletes the essential minerals in processed mushrooms (Drewnowska et al., 2017). The study investigated the potential effect of stir-frying in deep oil using a traditional Chinese wok on Hg content in boletus mushrooms collected in the Yuxi county in the Chinese province of Yunnan in July 2017.

2. Materials and methods

2.1. Raw mushrooms

The mushrooms examined were species such as *Baorangia bicolor* (Kuntze) G. Wu, Halling & Zhu L. Yang [previous name *Boletus bicolor* Peck], (Jiangchuan, Shihe n = 11 and Dayingjie, Luohe n = 16), *Boletus calopus* Fr. (Jiangchuan, Anhua; n = 22), *Boletus flammans* Dick & Snell (Linxiu; n = 15), *Boletus obsclereumbrinus* Hongo. (Jiangchuan, Shihie; n = 13), *Rubroboletus sinicus* (W.F. Chiu) Kuan Zhao & Zhu L. Yang (Hongta, Huangcaoba; n = 7) and *Boletus speciosus* Forst. (Jiangchuan, Shihie; n = 10), *Rugiboletus extremiorientalis* (Lj.N. Vassiljeva) G. Wu & Zhu L. Yang [previous name *Leccinum extremiorientale* (L. Vass.) Singer.] (Dayingjie, Luohe; n = 5 and Jiangchuan, Anhua; n = 15)- and unidentified *Xerocomus* sp. (Dayingjie, Luohe; n = 10) (Table 1).

Mushrooms came from the Yuxi region localized in the middle of Yunnan and were harvested in July 2017. Fruiting bodies (from 5 to 23 relatively young individuals in a pool) were cleaned-up from the soil particle debris, separated for caps and stipes and sliced. Moisture content of each pooled sample of caps and stipes was determined gravimetrically by oven-drying of the subsamples for 24 h to a constant weight at 65 °C in a food dehydrator (Ultra FD1000, Ezidri, Australia). Dried mushrooms were grounded to fine powder using a porcelain mortar and pestle and were kept in sealed polyethylene bags in dry and clean condition until instrumental analysis.

2.2. Mushroom dishes

The mushroom recipes used the same species as listed in Section 2.1. Mushrooms (from 7 to 23 specimens per species) were collected from the same places and in the same time as the uncooked individuals and were from the same suppliers. Both, uncooked and cooked specimens were of similar size (young fruiting bodies) (Table 1). The whole fruiting bodies were sliced and stir-fried in deep oil (200 mL) in a wok. Frying time was around 10 min. Fried mushrooms were drained from the oil used for cooking, dehydrated, ground and kept deep frozen (minus 20 °C) in tightly closed polyethylene jars until analysis.

2.3. Mercury determination and AC/AQ protocol

The determination of Hg in dehydrated fungal materials was performed using cold-vapour atomic absorption spectroscopy (CV-AAS) by a direct sample thermal decomposition coupled with a gold wool trap of Hg, and its further desorption and quantitative measurement at wavelength of 253.7 nm. Each sample was examined at least in triplicate and most of the samples, because of unexpectedly high Hg concentrations, 4–5 replicate analyses were performed. The analytical instrument used was a mercury analyzer (MA-2000, Nippon Instruments Corporation, Takatsuki, Japan) equipped with an auto-sampler, and operated in low or high modes, as appropriate (Falandysz et al., 2015a).

Mercury recovery for a certified reference material (CS-M-3, dried mushroom powder *B. edulis*; n = 10), produced by the Institute of Chemistry and Nuclear Technology in Warsaw (Poland), tested in parallel with experimental mushrooms, amounted to 99.9% (certified value of Hg was 2.849 mg kg^{-1} and determined value was 2.845 ± 0.066 mg kg^{-1}; CV = 2.31%). The limit of detection (LOD) was 0.003 mg Hg/kg^{-1} db, and the limit of quantification (LOQ) was 0.005 mg kg^{-1} db. One blank sample and one certified reference material sample were examined with each set of 2–3 experimental samples studied.

3. Results and discussion

The fresh and cooked mushrooms represented different collections of the same species and are treated separately. Both uncooked and

Table 1
Mercury content (mg kg^{-1} dry biomass; means ± S.D. and medians) in composite samples of raw and stir-fried in deep oil mushrooms from the Yuxi region in Yunnan, China.

Species and site	Raw mushrooms				Fried mushrooms
	Caps	Stipes	Whole	*$Q_{C/S}$	Whole
Boletus calopus	2.7 ± 0.1#	1.4 ± 0.0	2.1 ± 0.1	1.8 ± 0.0	0.83 ± 0.02
Jiangchuan, Anhua	2.7	1.4	2.1	1.8	0.83
Boletus bicolor	3.6 ± 0.1	1.4 ± 0.1	2.7 ± 0.1	2.5 ± 0.1	0.97 ± 0.02
Jiangchuan, Shihe	3.5	1.4	2.5	2.5	0.97
Boletus bicolor	2.0 ± 0.1	0.80 ± 0.02	1.8 ± 0.1	2.5 ± 0.1	1.1 ± 0.0
Dayingjie, Luohe	2.0	0.79	1.7	2.5	1.1
Boletus flammans	2.3 ± 0.1	1.6 ± 0.1	2.0 ± 0.1	1.5 ± 0.1	0.98 ± 0.02
Linxiu	2.4	1.5	2.0	1.5	0.98
Xerocomus sp.	11 ± 0	6.7 ± 0.4	10 ± 0	1.6 ± 0.0	3.2 ± 0.1
Dayingjie, Luohe	11	6.8	9.8	1.6	3.2
Leccinum extremiorientale	4.2 ± 0.2	1.6 ± 0.1	2.5 ± 0.2	2.7 ± 0.1	1.6 ± 0.1
Dayingjie, Luohe	4.2	1.6	2.5	2.8	1.6
Leccinum extremiorientale	4.6 ± 0.2	1.8 ± 0.1	4.2 ± 0.2	2.6 ± 0.0	2.6 ± 0.2
Jiangchuan, Anhua	4.6	1.8	4.2	2.6	2.6
Boletus obsclereumbrinus	0.71 ± 0.03	0.33 ± 0.02	0.53 ± 0.02	2.1 ± 0.1	5.1 ± 0.2
Jiangchuan, Shihe	0.72	0.34	0.54	2.1	5.2
Boletus speciosus	1.6 ± 0.0	1.1 ± 0.4	1.4 ± 0.0	1.4 ± 0.0	0.78 ± 0.02
Jiangchuan, Shihe	1.6	1.1	1.4	1.4	0.78
Rubroboletus sinicus	4.5 ± 0.2	2.5 ± 0.1	3.5 ± 0.1	1.7 ± 0.1	3.4 ± 0.1
Hongta, Huangcaoba	4.6	2.5	3.6	1.7	3.5

Each result for composite sample was obtained in 3 to -5 replicates.
* $Q_{C/S}$ (quotient from concentration of Hg in caps and stipes).

cooked mushroom materials were characterized by a relatively high Hg content (Table 1).

3.1. Raw mushrooms

The caps of the fruiting bodies contained between 1.4 (*B. speciosus*) to 2.8 (*L. extremiorientale*) times more Hg than the stems (Table 1; median values). The median values of Hg content determined in caps were in the range from 0.71 mg kg^{-1} db (*B. obsclereumbrinus*) to 11 mg kg^{-1} db (*Xerocomus* sp.), and in stems, median values were in the range from 0.33 mg kg^{-1} db (*B. obsclereumbrinus*) to 6.8 mg kg^{-1} db (*Xerocomus* sp.). The median values of Hg content calculated for the whole fruiting bodies were in the range from 0.72 mg kg^{-1} db (*B. speciosus*) to 9.8 mg kg^{-1} db (*B. obsclereumbrinus*) (Table 1). Humidity of raw mushrooms ranged from 90 to 92% (average 91%).

The median values of the Hg content of caps, calculated on the basis of fresh biomass, were in the range from 0.046 mg kg^{-1} (*B. obsclereumbrinus*) to 0.96 mg kg^{-1} (*Xerocomus* sp.), and in concentrations in stems ranged from 0.029 mg kg^{-1} (*B. obsclereumbrinus*) to 0.58 mg kg^{-1} (*Xerocomus* sp.). Median values of Hg content in the whole fruiting bodies, calculated on the basis of fresh biomass, were in the range from 0.046 mg kg^{-1} (*B. speciosus*) to 0.75 mg kg^{-1} (*Xerocomus* sp.) (Table 2).

Data on the high content of Hg in the raw boletes mushrooms obtained in this study (Table 1) largely agree with the previously published results (Falandysz et al., 2015a,b, 2016; Kojta et al., 2015). They confirm that mushrooms collected from certain regions of the Yuxi prefecture in Yunnan can contain relatively high concentrations of this element. Due to the size of the mountainous region (15,285 km^2) and because of the numerous areas where wild mushrooms can be harvested and sold, more systematic studies would be needed to include the soil substrate to obtain a better spatial image of Hg accumulation in edible mushrooms to cover the entire region.

3.2. Mushroom meals

The median values of Hg content in mushroom meals (prepared using whole fruiting bodies), when presented on a dry biomass basis, were in the range from 0.78 mg kg^{-1} (*B. speciosus*) to 5.2 mg kg^{-1} (*B. obsclereumbrinus*) (Table 1). It should be noted that the batches of raw and fried mushrooms represented different collections of the same species, and thus the results of the determinations reflected the natural heterogeneity and variability of the Hg content between them. When the results are presented in terms of dry biomass, stir-fried mushrooms

Table 2
Mercury content in fresh mushrooms and in fried mushroom- meals (μg kg^{-1} whole weight) from the Yuxi region of Yunnan, China and estimated daily and weekly Hg intake with the mushroom meals.

Species	Hg in fresh mushrooms	Hg in fried mushrooms	Hg intake (μg) with 100 g × 1 fried mushrooms	Hg intake (mg) with 100 g × 7 fried mushrooms	Estimated daily Hg intake (μg kg^{-1} bm) by adult (100 g × 1); RfD for Hg is 0.3 μg kg^{-1} bm	Estimated weekly Hg intake (μg kg^{-1} bm) by adult (100 g × 7); PTWI for inorganic Hg is 4 μg kg^{-1} bm
B. calopus	190	350	35	245	0.58	4.1
B. bicolor	230	540	54	378	0.90	6.3
B. bicolor	160	610	61	427	1.0	7.1
B. flammans	190	420	42	294	0.70	4.9
Xerocomus sp.	750	1400	140	980	2.3	16.3
R. extremiorientalis	260	750	75	525	1.2	8.7
L. extremiorientale	430	1200	120	840	2.0	14
B. obsclereumbrinus	46	2200	220	1540	3.7	25.7
B. speciosus	140	330	33	231	0.55	3.8
R. sinicus	300	1500	150	1050	2.5	17.5

were less contaminated with Hg than dried raw mushrooms. A notable exception was for dishes made of the fried *B. obsclereumbrinus*, which showed Hg at 7-fold greater content when compared to dried (raw) mushrooms, while for *R. sinicus* the contents were similar (Table 1). The results confirm that not only raw mushrooms, but also stir-fried in deep oil mushroom meals can be substantially contaminated with Hg in some parts of Yunnan province.

Slicing and stewing of fresh mushrooms promotes leaking of juice and soluble compounds and colloids during cooking. If the whole fresh mushrooms or their parts are deep frozen and further thawed the juice and soluble compounds can leak out through broken cell walls before they undergo further treatment (Svoboda et al., 2002).

In an experimental cooking process, conducted over three separate trials, the frozen (−20 °C) whole fruiting bodies of *Imleria badia* (former name *Xerocomus badius*) and *Xerocomus chrysenteron* respectively were thawed, homogenized (for 10 min by using a mixer), divided into portions (50 g), poured into a glass bakers (250 mL) and cooked (under continuous stirring) for 20 min using a hot plate heated to 300 °C (Cibulka et al., 1999). In the above experiment, Hg content of the homogenates decreased respectively by 28% (drop from 1.83 to 1.31 mg kg^{-1}), 37% (drop from 1.76 to 1.10 mg kg^{-1}) and 49% (drop from 2.45 to 1.26 mg kg^{-1}). It was thought that this could possibly be due to co-evaporation with moisture. Stir-fried mushrooms in this study lost a portion of moisture (42% of biomass, on the average), whilst they absorbed a substantial amount of oil.

Few data are available about the loss of Hg for only a handful of species in the course of typical domestic treatment (Falandysz and Drewnowska, 2015, 2017; Svoboda et al., 2002). A decrease in concentration of Hg from after blanching of fresh sliced *I. badia* was around 15% and around 22% after blanching of sliced and deep frozen individuals (Svoboda et al., 2002).

Blanching of sliced *C. cibarius* decreased the content of Hg by approximately by 15%, but this was up to 35% when the mushrooms were sliced and kept deep-frozen and further blanched -. Pickling the mushrooms only slightly increased the loss of the contaminant with medians in the range 13 to 34% for fresh and blanched, and 34 to 39% for deep-frozen and blanched (Falandysz and Drewnowska, 2017). For experiments with *Amanita fulva,* blanching decreased Hg by 10% (halves of the whole fruit bodies) and by 56 ± 2% (quarters of caps) (Falandysz and Drewnowska, 2015, 2017). As it was in the case of *C. cibarius*, pickling had little if any effect on further removal of Hg from the blanched *A. fulva*.

Meals prepared by stir-frying bolete mushrooms are tasty and due to absorbed oil are around 4-fold more calorific than uncooked mushrooms. A wok-pan style stir-frying of mushrooms requires a higher temperature regime (average is 175 °C; Bordin et al., 2013), if compared to blanching at 100 °C. This can result in a higher rate of leaching of the elements from the flesh of the mushroom to an oily phase or/and possible co-evaporation with water. A large portion of moisture (up to around 50%) can evaporate from mushrooms in the course of stir-frying in deep oil, while in the same time, oil is absorbed by mushrooms at rate of around 25%. Mushrooms, are a low calorie foodstuff, e.g. the boletes have around 34 to 52 kcal (144 to 219 kJ) per 100 g fresh biomass (Liu et al., 2016). When stir-fried in deep oil, mushrooms become much more nutritious in terms of calories than raw or boiled produce (around 220 kcal can be added as a result of absorption of vegetable oil per 100 g of fresh mushrooms).

An open question remains about whether the oil used for cooking is discarded or used to any extent to create further dishes. Discarding the used oil can reduce the intake of Hg from mushrooms (other vegetables if added to a meal are commonly around ten time less in Hg when compared to mushrooms). A standardization of a cooking procedures for mushrooms fried with a wok using vegetable oil (and other vegetables) seems difficult regarding to a local practice in China, whilst the present study calls for a better insight into the impact on many types of local foods.

The pan-frying (with a small amount of vegetable oil and salt) of *C. cibarius* and *B. edulis* removed from 18 to 29% and 9% of radiocaesium (^{137}Cs) (Steinhauser and Steinhauser, 2016), respectively into the juice. These elements therefore seem to occur in mushrooms in forms that are more soluble in water when compared to Hg. A small amount of oily residue produced (for chanterelles or *L. delicious* often butter is used instead of a vegetable oil) should be discarded to minimise exposure to Hg but because of its culinary properties, it is usually is eaten, typically with bread.

In spite of the possibility to deplete Hg from the mushroom by transfer to oil used for stir-frying, and due to the possibility of co-evaporation with water during high temperature cooking (Bordin et al., 2013), this procedure can concentrate Hg in the final product (due to partial dehydration of the fungal substrate) when data are expressed on a product (ready-to-eat mushrooms) weight basis. A real impact of the stir-frying in deep oil regarding the fate and potential to decrease the Hg content (oil phase/co-evaporation) has to be clarified from the ongoing study.

3.3. *Mercury intake with mushroom meals*

The acceptable daily intake (reference dose; RfD) for inorganic Hg for adults is 0.3 μg kg^{-1} body mass (US EPA, 1987) and the Provisionally Tolerable Weekly Intake (PTWI) is 4.0 μg kg^{-1} body mass) (WHO, 2018). Mushrooms that have been stir-fried in deep oil are a kind of a "ready to eat" food. Usually, in the late phase of 10 min frying, spices (small hot dried red chili peppers, salt) are added to the mushrooms, and oil that is not absorbed is drained out and the mushrooms served. To assess any possible adverse health risk due to the intake of Hg contained in such mushroom dishes in this study, both approaches have been applied.

A portion of 100 g fried mushrooms (whole weight) eaten daily per capita per week (100 g × 7) was used to estimate exposure to Hg associated with dietary intake of mushrooms in Yunnan. Nevertheless, in some studies an amount of 300 g was used to estimate daily intake of Hg with mushroom meals for high consumers who might eat mushrooms on a regular basis (Zhang et al., 2010). Table 2 shows that a 100 g portion per day will provide from 33 to 220 μg of Hg, and in the course of a week, the intake will be from 231 to 1540 μg of Hg solely from mushrooms.

The assessed Hg intakes resulting from the consumption of 100 g × 1 daily or 100 g × 7 in a week (Table 2) by an adult of 60 kg body mass are equivalent, respectively, to the doses in the range from 0.55 to 3.7 μg kg^{-1} body mass (RfD is 0.3 μg kg^{-1} body mass), and from 3.8 to 26 μg kg^{-1} body mass (PTWI is 4.0 μg kg^{-1} body mass). Those values for mushroom meals (Table 2) clearly often exceed the existing the RfD or PTWI criteria for safe Hg intake. Vegetarians and vegans can be seen as potential groups of consumers in southwestern China that eat more fried mushrooms than the assumed 100 g × 1 daily or 100 g × 7 in a week, and hence will be exposed to Hg doses well above the RfD or PTWI with a potential threat to health.

4. Conclusions

To our knowledge, this is the first study on Hg in stir-fried in deep oil mushroom meals and on the possible impact of stir-frying on Hg content in mushrooms as consumed. Mushrooms have a naturally high background content of Hg from the geochemically anomalies in several populated regions of the World. The process of stir-frying in deep oil seems to decrease the content of Hg in fried mushrooms if data for both uncooked (raw) and cooked (fried) mushrooms are expressed on a dry biomass (weight) basis. On the other hand, stir-frying in deep oil clearly concentrates Hg (due to a partial dehydration of the fungal substrate and limited loss of Hg) in a real mushroom meal (product weight basis). The effect of the stir-frying in deep oil process on Hg content has to be clarified from the ongoing studies. Meals made of the stir-fried bolete mushrooms collected from the geochemically anomalous regions in the southwestern Asia and including the Yunnan province is a source of potential exposure to Hg to consumers and doses may exceed current recommended maximum levels. Thus, more information is required on both behaviours of Hg during cooking and data is needed on intake, including bioavailability and bioaccessibility of Hg from the fried mushroom meals in future studies.

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References

Árvay, J., Tomáš, J., Hauptvogl, M., Kopernická, M., Kováčik, A., Bajčan, D., Massányi, P., 2014. Contamination of wild-grown edible mushrooms by heavy metals in a former mercury-mining area. J. Environ. Sci. Health B 49, 815–827.

Bordin, K., Kunitake, M.T., Aracava, K.K., Trindade, C.S., 2013. Changes in food caused by deep fat frying - a review. Arch. Latinoam. Nutr. 63, 5–13.

CEFA, 2016. China Edible Fungi Association. (viewed 27 December 2018). http://www.cefa.org.cn/2017/10/24/10250.html.

Cibulka, J., Čudrova, E., Miholová, D., Stěhulová, I., 1999. Mercury loss from edible mushrooms after their model thermal treatment. Czech J. Food Sci. 17, 238–240.

Crane, S., Dighton, J., Barkay, T., 2010. Growth responses to and accumulation of mercury by ectomycorrhizal fungi. Fungal Biol. 114, 873–880.

Drewnowska, M., Falandysz, J., Chudzińska, M., Hanć, A., Saba, M., Barałkiewicz, D., 2017. Leaching of arsenic and sixteen metallic elements from *Amanita fulva* mushrooms after food processing. LWT – Food Sci. Technol. 84, 861–866.

Falandysz, J., 2008. Selenium in edible mushrooms. J. Environ. Sci. Health C 26, 256–299.

Falandysz, J., 2016. Mercury bio-extraction by fungus *Coprinus comatus*: a possible bioindicator and mycoremediator of polluted soils. Environ. Sci. Pollut. Res. 23, 7444–7451.

Falandysz, J., 2017. Mercury accumulation of three *Lactarius* mushroom species. Food Chem. 214, 96–101.

Falandysz, J., Borovička, J., 2013. Macro and trace mineral constituents and radionuclides in mushrooms: health benefits and risks. Appl. Microbiol. Biotechnol. 97, 477–501.

Falandysz, J., Drewnowska, M., 2015. Distribution of mercury in *Amanita fulva* (Schaeff.) Secr. mushrooms: accumulation, loss in cooking and dietary intake. Ecotoxicol. Environ. Saf. 115, 49–54.

Falandysz, J., Drewnowska, M., 2017. Cooking can decrease mercury contamination of a mushroom meal: *Cantharellus cibarius* and *Amanita fulva*. Environ. Sci. Pollut. Res. 24, 13352–13357.

Falandysz, J., Gucia, M., Frankowska, A., Kawano, M., Skwarzec, B., 2001. Total mercury in wild mushrooms and underlying soil substrate from the city of Umeå and its surroundings, Sweden. Bull. Environ. Contam. Toxicol. 67, 763–770.

Falandysz, J., Brzostowski, A., Kawano, M., Kannan, K., Puzyn, T., Lipka, K., 2003. Concentrations of mercury in wild growing higher fungi and underlying substrate near Lake Wdzydze, Poland. Water Air Soil Pollut. 148, 127–137.

Falandysz, J., Gucia, M., Mazur, A., 2007a. Content and bioconcentration factors of mercury by Parasol Mushroom *Macrolepiota procera*. J. Environ. Sci. Health B 42, 735–740.

Falandysz, J., Frankowska, A., Mazur, A., 2007b. Mercury and its bioconcentration factors in King Bolete (*Boletus edulis*) Bull. Fr. J. Environ. Sci. Health A 42, 2089–2095.

Falandysz, J., Lipka, K., Mazur, A., 2007c. Mercury and its bioconcentration factors in Fly Agaric (*Amanita muscaria*) from spatially distant sites in Poland. J. Environ. Sci. Health A 42, 1625–1630.

Falandysz, J., Kunito, T., Kubota, R., Lipka, K., Mazur, A., Falandysz, J.J., Tanabe, S., 2007d. Selected elements in fly agaric *Amanita muscaria*. J. Environ. Sci. Health A 42, 1615–1623.

Falandysz, J., Zhang, J., Wang, Y., Krasińska, G., Kojta, A., Saba, M., Shen, T., Li, T., Liu, H., 2015a. Evaluation of the mercury contamination in mushrooms of genus *Leccinum* from two different regions of the world: accumulation, distribution and probable dietary intake. Sci. Total Environ. 537, 470–478.

Falandysz, J., Zhang, J., Wang, Y., Saba, M., Krasińska, G., Wiejak, A., Li, T., 2015b. Evaluation of the mercury contamination in Fungi *boletus* species from latosols, lateritic red earths, and red and yellow earths in the Circum-Pacific Mercuriferous Belt of Southwestern China. PLoS One 10 (11), e0143608. https://doi.org/10.1371/journal.pone.0143608.

Falandysz, J., Saba, M., Liu, H.-G., Li, T., Wang, J., Wiejak, A., Zhang, J., Wang, Y.-Z., Zhang, D., 2016. Mercury in forest mushrooms and topsoil from the Yunnan highlands and the Subalpine region of the Minya Konka Summit in the Eastern Tibetan Plateau. Environ. Sci. Pollut. Res. 23, 23730–23741.

Falandysz, J., Zhang, J., Wiejak, A., Barałkiewicz, D., Hanć, A., 2017. Metallic elements and metalloids in *Boletus luridus*, *B. magnificus* and *B. tomentipes* mushrooms from polymetallic soils from SW China. Ecotoxicol. Environ. Saf. 142, 497–502.

Falandysz, J., Mędyk, M., Treu, R., 2018. Bio-concentration potential and associations of heavy metals in *Amanita muscaria* (L.) Lam. from northern regions of Poland. Environ. Sci. Pollut. Res. 25, 25190–25206.

Falandysz, J., Zhang, J., Mędyk, M., Zhang, X., 2019. Mercury in stir-fried and raw mushrooms from the Boletaceae family from the geochemically anomalous region in the Midu county, China. Food Control 102, 17–21.

Gabriel, J., Švec, K., Kolihová, K., Tlustoš, P., Száková, J., 2016. Translocation of mercury from substrate to fruit bodies of *Panellus stipticus*, *Psilocybe cubensis*, *Schizophyllum commune* and *Stropharia rugosoannulata* on oat flakes. Ecotox. Environ. Saf. 125, 184–189.

Kavčič, M., Petric, M., Vogel-Mikuš, K., 2018. Chemical speciation using high energy resolution PIXE spectroscopy in the tender X-ray range. Nucl. Instrum. Methods Phys. Res. B 417, 65–69.

Kojta, A.K., Wang, Y., Zhang, J., Li, T., Saba, M., Falandysz, J., 2015. Mercury contamination of fungi genus *Xerocomus* in the Yunnan Province in China and the region of Europe. J. Environ. Sci. Health A 50, 1342–1350.

Kojta, A.K., Falandysz, J., 2016. Soil-to-mushroom transfer and diversity in total mercury content in two edible Laccaria mushrooms. Environ. Earth Sci. 75 (18), 1264.

Komorowicz, I., Hanć, A., Lorenc, W., Barałkiewicz, D., Falandysz, J., Wang, Y., 2019. Arsenic speciation in mushrooms using dimensional chromatography coupled to ICP-MS detector. Chemosphere 233, 223–233. https://doi.org/10.1016/j.chemosphere.2019.05.130.

Krasińska, G., Falandysz, J., 2015. Mercury in Hazel Bolete *Leccinum griseum* and soil substratum: distribution, bioconcentration and probable dietary exposure. J. Environ. Sci. Health A 50, 1259–1264.

Krasińska, G., Falandysz, J., 2016. Mercury in Orange Birch Bolete *Leccinum versipelle* and soil substratum: Bio-concentration by mushroom and probable dietary intake by consumers. Environ. Sci. Pollut. Res. 23, 860–869.

Li, M., Wang, P., Wang, J., Chen, X., et al., 2018. Arsenic concentrations, speciation, and localization in 141 cultivated market mushrooms: implications for arsenic exposure to humans. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b05206.

Lipka, K., Falandysz, J., 2017. Accumulation of metallic elements by *Amanita muscaria* from rural lowland and industrial upland regions. J. Environ. Sci. Health B 52, 184–190.

Lipka, K., Saba, M., Falandysz, J., 2018. Preferential accumulation of inorganic elements in *Amanita muscaria* from North-eastern Poland. J. Environ. Sci. Health A 53, 968–974.

Liu, Y., Chen, D., You, Y., Zeng, S., et al., 2016. Nutritional composition of boletus mushrooms from Southwest China and their antihyperglycemic and antioxidant activities. Food Chem. 211, 83–91.

Melgar, M.J., Alonso, J., García, M.Á, 2009. Mercury in edible mushrooms and soil. Bioconcentration factors and toxicological risk. Sci. Total Environ. 407, 5328–5334.

Nasr, N., Arp, P.A., 2011. Hg concentrations and accumulations in fungal fruiting bodies, as n m influenced by forest soil substrates and moss carpets. Appl. Geochem. 26, 1905–1917.

Nasr, M., Malloch, D.W., Arp, P.A., 2012. Quantifying Hg within ectomycorrhizal fruiting bodies, from emergence to senescence. Fungal Biol. 116, 1163–1177.

Ostos, C., Pérez-Rodríguez, F., Baldomero, F.P., Moreno Arroyo, B., Moreno-Rojas, R., 2015. Study of mercury content in wild edible mushrooms and its contribution to the Provisional Tolerable Weekly Intake in Spain. J. Food Anal. 37, 136–142.

Pankavec, S., Hanć, A., Barałkiewicz, D., Dryżałowska, A., Zhang, J., Falandysz, J., 2019. Mineral constituents of conserved white button mushrooms: similarities and differences. Roczn. Państw. Zakł. Hig (Ann. Nat. Inst. Hyg.) 70, 15–25.

Rzymski, P., Mleczek, M., Siwulski, M., Gąsecka, M., Niedzielski, P., 2016. The risk of high mercury accumulation in edible mushrooms cultivated on contaminated substrates. J. Food Anal. 51, 55–60.

Steinhauser, G., Steinhauser, V., 2016. A simple and rapid method for reducing radiocesium concentrations in wild mushrooms (*Cantharellus* and *Boletus*) in the course of cooking. J. Food Prot. 79, 1995–1999.

Stijve, T., Roschnik, R., 1974. Mercury and methyl mercury content of different species of fungi. Travaux de chimie alimentaire et d'hygiène 65, 209–220.

Svoboda, L., Kalač, P., Špička, J., Janoušková, D., 2002. Leaching of cadmium, lead and mercury from fresh and differently preserved edible mushroom, *Xerocomus badius*, during soaking and boiling. Food Chem. 79, 41–45.

Tuzen, M., Soylak, M., 2005. Mercury contamination in mushroom samples from Tokat, Turkey. Bull. Environ. Chem. Toxicol. 74, 968–972.

US EPA, 1987. Peer Review Workshop on Mercury Issues. Environmental Criteria and Assessments Office. Summary Report. US Environment Protection Agency, Cincinnati.

Vogel-Mikuš, K., Debeljak, M., Kavčič, A., Murn, T., Arčon, I., Kodre, A., van Elteren, J.T., Budič, B., Kump, P., Mikuš, K., Migliori, A., Czyzycki, M., Karydas, A., 2016. Localization and bioavailability of mercury and selenium in edible mushrooms *Boletus edulis* and *Scutiger pes caprae*. Abstract Book of the 18th International Conference on Heavy Metals in the Environment, 12 to 15 September 2016 611–612.

Wang, X.M., Zhang, J., Wu, L.H., Zhao, Y.L., Li, T., Li, J.Q., Wang, Y.Z., Liu, H.G., 2014. A mini-review of chemical composition and nutritional value of edible wild-grown mushroom from China. Food Chem. 15 (151), 279–285.

WHO, 2018. World Health Organization. (viewed 27 December 2018). http://apps.who.int/food-additives-contaminants-jecfa-database/chemical.aspx?chemID=1806.

Wiejak, A., Wang, Y.-Z., Zhang, J., Falandysz, J., 2016. Mercury in sclerotia of *Wolfiporia extensa* (Peck) Ginns fungus collected across of the Yunnan land. Spectr. Spec. Anal. 36, 3083–3086.

Wu, G., Y-Ch, Li, Zhu, X.-T., et al., 2016. One hundred noteworthy boletes from China. Fungal Divers. 81, 25–188.

Zhang, D., Frankowska, A., Jarzyńska, G., Kojta, A.K., Drewnowska, M., Wydmańska, D., Bielawski, L., Wang, J., Falandysz, J., 2010. Metals of King Bolete (*Boletus edulis*) collected at the same site over two years. Afr. J. Agric. Res. 5, 3050–3055.

Zhang, J., Li, T., Yang, Y.L., Liu, H.G., Wang, Y.Z., 2015. Arsenic concentrations and associated health risks in Laccaria mushrooms from Yunnan (SW China). Biol. Trace Elem. Res. 164, 261–266.