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Mini-review

Toxicological Profiles of Poisonous, Edible, and Medicinal Mushrooms

Woo-Sik Jo[1,†], Md. Akil Hossain[2,†] and Seung-Chun Park[2,*]

[1]*Department of Agricultural Environment, Gyeongbuk Agricultural Technology Administration, Daegu 702-320, Korea*
[2]*Laboratory of Clinical Pharmacokinetics and Pharmacodynamics, College of Veterinary Medicine, Kyungpook National University, Daegu 702-701, Korea*

Abstract Mushrooms are a recognized component of the human diet, with versatile medicinal properties. Some mushrooms are popular worldwide for their nutritional and therapeutic properties. However, some species are dangerous because they cause toxicity. There are many reports explaining the medicinal and/or toxic effects of these fungal species. Cases of serious human poisoning generally caused by the improper identification of toxic mushroom species are reported every year. Different substances responsible for the fatal signs and symptoms of mushroom toxicity have been identified from various poisonous mushrooms. Toxicity studies of mushroom species have demonstrated that mushroom poisoning can cause adverse effects such as liver failure, bradycardia, chest pain, seizures, gastroenteritis, intestinal fibrosis, renal failure, erythromelalgia, and rhabdomyolysis. Correct categorization and better understanding are essential for the safe and healthy consumption of mushrooms as functional foods as well as for their medicinal use.

Keywords Mushroom toxicity, Poisonous mushroom, Toxic compounds

Poisoning is an important global public health problem. It recently became the leading cause of injury death for the first time since at least 1980. According to a report of the Centers for Disease Control and Prevention (CDC), more than 41,000 people have died in 2008 because of unintentional poisoning, while the World Health Organization (WHO) has reported 0.346 million deaths since 2004 worldwide [1]. A significant portion of these global numbers is attributable to mushroom poisoning. There are numerous mushroom poisoning cases in different countries each year. In 1998, 1,675 mushroom poisoning cases were reported in France and approximately 8,000 to 10,000 cases are estimated to be on record.

Mushrooms have long attracted a great deal of interest in many areas of the food and biopharmaceutical industries. They are well known for their nutritional and medicinal values [2, 3]. The worldwide diversity of mushroom species is roughly accounted as 0.14 million. Of these, 14,000 are known and 7,000 are considered to have varying levels of edibility. More than 2,000 species are safe and 700 are documented to have considerable pharmacological properties [2, 4-6].

A series of species have been characterized as hazardous to health and defined as toxic species. Toxic substances are also found in some mushroom species with beneficial properties [7]. The ingestion of mushrooms containing toxins is accidental and often occurs through the misidentification of species [8, 9]. This accidental event frequently occurs due to insufficient available data on poisonous mushrooms, including information on potential toxicity [9, 10]. It is critical to characterize the toxicological profile of mushroom species before using them for human consumption. The aim of the current study is to review the poisonous substances present in different species of edible, medicinal, and poisonous mushrooms.

POISONOUS SUBSTANCES IN MUSHROOMS

Several exceptionally potent toxins have already been identified from a number of mushrooms (Table 1). Even consumption of a small amount can be dangerous for humans. Mushroom toxidromes are classified according to the toxins involved and clinical presentations (Table 1). Mushroom toxins have been divided into seven main categories: amatoxins

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***Corresponding author**
E-mail: parksch@knu.ac.kr
[†]These authors contributed equally to this paper.

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(cyclopeptides), orellanus (*Cortinarius* species), gyromitrin (monomethylhydrazine), muscarine, ibotenic acid, psilocybin, and coprine [11]. A discussion of these toxins follows, including their sources, molecular properties, clinical manifestations, mechanisms, and potential toxicity (Table 1 and 2).

All amatoxin-containing fungi are found within the families Amanitaceae (genus *Amanita*), Agaricaceae (genus *Lepiota*), and Cortinariaceae (genus *Galerina*). Some species of *Amanita* such as *Amanita virosa, A. phalloides, A. ocreata, A. verna*, *A. subalbiacea, A. bisporigera, A. hygroscopica*, and *A. tenuifolia* are abundant in amatoxins. Amatoxins are bicyclic octapeptides and powerful thermostable poisons [12]. The most potent amatoxin is α-amanitine, and is among the nine amatoxins that have been recognized. Ataxia, motor depression, euphoria, dizziness, gastrointestinal disturbances, drowsiness, muscle twitches, and changes in insight, feelings, and mood are common symptoms associated with amatoxin poisoning [13-15]. The molecular mechanism of amatoxin action is inhibition of DNA-dependent RNA polymerase-II (Table 2). Depletion of mRNA levels leads to reduced protein synthesis and ultimately the affected cells undergo necrosis or apoptosis [12, 16]. Symptomatic treatments are mainly recommended for this poisoning, including the use of phenobarbitone or benzodiazepines during seizures [17, 18]. Detoxification at the beginning of treatment is essential in amatoxin-intoxicated patients and they need careful monitoring. Liver transplantation may be required in cases of severe poisoning [12].

Gyromitrin is an oxidizable volatile liquid at room temperature, making it an unstable chemical. The toxin gyromitrin is present in some species of *Gyromitra.* Ingestion of *Gyromitra*, and even the inhalation of vapors produced during the cooking of this mushroom, can cause toxicity

Table 1. Clinical manifestations, sites of toxicity, and toxicity potential of various mushroom species

Toxic syndrome	Toxins	Sites of toxicity	Species	Mortality rate	Reference
Acute gastroenteritis without liver failure	GI irritants	GIT	*Chlorophyllum molybdites*, *Clitocybe nebularis*, *Omphalotus illudens*	Rare	[19]
Hallucinogenic	Psilocybin, psilocin	CNS (hallucinogenic effects)	*Psilocybe cubensis*, *P. mexicana*, *Conocybe cyanopus, G. aeruginosa*	Rare	[20, 21]
CNS excitation and depression (stupor, coma, delirium, agitation, hallucinations and seizures)	Ibotenic acid, muscimol	CNS (depressant and excitatory effects)	*Amanita muscaria*, *A. pantherina*, *A. gemmata*	Rare	[22]
Cholinergic excess (vomiting, diarrhea, bradycardia, bronchorrhea, tearing, bronchospasm, salivation)	Muscarine	Autonomic nervous system (muscarinic receptors)	*Clitocybe dealbata*, *C. illudens*, *I. fastigiata*, *Boletus calopus*	Rare	[20, 21]
Flushing, headache, tachycardia, chest pain, anxiety	Coprine	-	*Coprinus atramentarius*	Rare	[20, 21]
Gastroenteritis and delayed onset renal failure	Allenic norleucine	Kidney, GIT	*Amanita smithiana*	Rare	[20, 21]
Delayed liver toxicity and delayed gastroenteritis	Amatoxins, phallotoxins	GIT, liver, kidney	*Amanita phalloides*, *A. virosa*, *A. verna*, *A. bisporigera*, *Galerina autumnalis*, *G. marginata, G. venenata*, *Lepiota helveola*	2~30%	[23, 24]
Seizures, delayed gastroenteritis, and liver toxicity	Gyromitrin	GIT, CNS, liver and blood	*Gyromitra esculenta*, *G. infula*, *Sarcosphaera coronaria*, *Chrysina macropus*	0~10%	[20, 21]
Delayed renal failure, cellular and oedematous intestinal fibrosis	Orellanine, orellinine, cortinarin	Kidney, GIT	*Cortinarius orellanus*, *C. speciosissinus*, *Mycena pura*, *O. orarius*	Rare	[25]
Delayed rhabdomyolysis	Unknown	Muscle	*Tricholoma equestre*	25%	[26]
Erythromelalgia	Acromelic acid	Peripheral nerves, skin	*Clitocybe acromelalga*	Rare	[27]
Delayed encephalopathy (patients with renal failure)	Unknown	Encephalopathy	*Pleurocybella porrigens*	27%	
Abdominal pain, diarrhea, and intense sweating	-	-	*Clitocybe rivulosa*	-	[28]

GI, gastrointestinal; GIT, gastrointestinal tract; CNS, central nervous system.

Table 2. Molecular properties and mechanism of toxicity of different toxins found in various mushroom species

Toxin name	Sources	Molecular properties	Mechanism of toxicity	Reference
Ostreolysin	*Pleurotus ostreatus*	A 16-kDa acidic protein, is a member of the aegerolysin protein family. It contains 137 residues of amino acids 13 positively and 16 negatively charged residues.	Transient increase in arterial blood pressure and then a progressive fall to mid-circulatory pressure accompanied by bradycardia, myocardial ischemia, and ventricular extrasystoles. The hyperkalemia resulting from the hemolytic activity probably plays an important role in its toxicity.	[29, 30]
Amatoxin	Different species of *Amanita*	Thermostable bicyclic octapeptide. Nine amatoxins have been identified and α-amanitine is the most active.	Inhibit RNA polymerase-II and thus transcription of DNA occurs by protein synthesis and cell necrosis.	[16, 31]
Phallotoxin	*Amanita phalloides*	Peptides containing bicyclic-skeleton with a transannular thioether bridge.	Specific binding of the toxin to F-actin in liver cells, which consequently inhibits the depolymerization of F-actin into G-actin.	[32]
Agaritin	*Agaricus bisporus*	Is an L-glutamic acid (b-N-(g-L(+) glutamyl)-4-hydroxymethyl) phenylhydrazine).	Agaritine can be enzymatically activated to a mutagenic metabolite and can bind with DNA and form adducts.	[33, 34]
Orellanine	*Pleurotus ostreatus* and *Cortinarius orellanus*	Is a heat-stable bipyridine N-oxide. Orellanine chemically resembles the pyridine herbicides paraquat and diquat and is deoxidized to orelline that is non-toxic.	*In vitro* data strongly suggest that orellanine generates oxygen radicals at the target site through redox cycling and/or redox activation of iron. Further data from cellular systems indicate that a metabolite of the toxin can inhibit protein synthesis.	[35]
Gyromitrin	*Gyromitra esculenta*	Gyromitrin is a volatile liquid, which is quite unstable, oxidizes at room temperature, and exists free or bonded with glucosides.	The hydrazines are convulsants, and they react with pyridoxal phosphate to form a hydrazine, which results in the decreased activity of glutamic acid decarboxylase and diminished formation of GABA.	[36]
Acromelic acid	*Clitocybe acromelalga*	Is a member of kainoid family, a group of non-proteinogenic pyrolidine dicarboxylic acids.	Acromelic acid A exhibits neuroexcitatory activity, can bind glutamate receptors, mimics glutamic acid, causes characteristic behavior changes, and induced selective damage to the interneurons in the lower spinal cord when tested in an animal model.	[37]
Ibotenic acid	*Amanita muscaria* and *A. pantherina*	Is an α-amino-3-hydroxy-5-isoxazole acetic acid.	An NMDA receptor agonist. Because of the acidic property of the isoxazole moiety, it is similar to glutamic acid and mimics its effects in animals.	[14, 15]
Muscimol	*Amanita muscaria* and *A. pantherina*	It is a decarboxylated product of ibotenic acid.	This substance shows structural resemblance to GABA and imitates the action of this inhibitory neurotransmitter in the CNS.	[14, 15]
Muscarine	*C. serussata, C. dealbata, C. phyllophilla, C. rivulosa* and *A. muscaria*	It is tetrahydro-4-hydroxy-*N*,*N*,*N*-5-tetramethyl-2-furanmethanaminium.	Muscarine's structure is very similar to that of acetylcholine and it binds to the same receptors. It is not hydrolyzed by cholinesterase causing a parasympathomimetic symptomatology.	[31]
Psilocybin and psilocin	-	Component of the tyramine type, 4-phosphoryloxy-*N*,*N*-dimethyltryptamine	Cleavage of the phosphoric ester group by alkaline phosphatase and unspecific esterases indicates that psilocybin acts as a prodrug and that its hydroxyl metabolite psilocin the active agent. Activity of psilocybin is due to the activation of serotonin 2-A receptor.	[38, 39]

GABA, gamma-aminobutyric acid; NMDA, *N*-methyl-D-aspartate; CNS, central nervous system.

[9, 10]. Diarrhea, vomiting, fatigue, vertigo, ataxia, tremor, and nystagmus are the most common symptoms of this intoxication. Development of hemolysis and hepatic diseases of moderate severity may develop in some patents. Hydrazines, which have convulsant, cytotoxic, and irritating properties, can be formed by the hydrolysis of gyromitrin in the stomach after ingestion [9, 40]. Carcinogenesis is another adverse effect of gyromitrin. Symptoms of intoxication start 8~12 hr after ingestion. The antidote is pyridoxine.

Mushrooms containing coprine may cause addiction when taken with alcohol. This ingredient accumulates in the blood because of alcohol decomposition when alcohol ingestion occurs before, with, or after mushroom intake. *Coprinus atramentarius* mushrooms contain coprine. The antidote is not known. Some species of *Clitocybe* are responsible for causing muscarinic syndrome. Muscarine is abundant in *C. rivulosa*, *C. dealbata*, *C. cerussata*, *C. phyllophila*, and *C. candicans*. It is also present in *Amanita muscaria* and the *Inocybe* genus. Symptoms of muscarinic syndrome include increased pulse rate, headache, nausea, vomiting, dizziness, and rapid breathing. Affected patients may show hypersecretion, miosis, and gastrointestinal disturbance. Bradycardia and even collapse may occur in severe cases of intoxication with this poison [28].

The symptoms of muscarinic poisoning caused by ingestion of mushrooms are sweating, tearing, drooling, vomiting, diarrhea, blood pressure, and shortness of breath due to effects on the parasympathetic nervous system. Most patients recover within 24 hr, except in cases when the heart has stopped and the patient cannot be revived. Symptomatic treatment is recommended to treat this syndrome. Administration of atropine is recommended to neutralize the muscarinic effects [28]. Poisonous mushrooms also contain muscimol. It causes paralysis 20~22 min after ingestion by acting on the central nervous system. Muscimol can serve as an insecticide and can kill flies. The mushrooms containing muscimol are *Amanita muscaria* and *Tricholoma muscarium*. The antidote is physostigmine.

Psilocybin is found abundantly in the genus *Psilocybe* [41]. Common mushrooms that contain psylocibin include *P. bohemica*, *P. mexicana*, *P. semilanceata*, *P. baeocystis*, and *P. cubensis* [40]. The toxicity symptoms of psilocybin develop 30 min after ingestion of these mushrooms. Frequently reported symptoms of this intoxication include hypertension, tachycardia, visual problems, nausea, anxiety, asthenia, vertigo, mydriasis, motor incoordination, and disorientation. Psilocybin toxicity-associated problems resolve completely 4~12 hr after ingestion. Generally, hospitalization is not required and myocardial infarction in adults after intoxication with psilocybin-containing mushrooms is rare. Coma, hyperthermia, and seizures may occur in children [40].

Indole derivative-containing psilocin mushrooms are usually blue in color. Symptoms of psilocin toxicity include curly limbs, tongue anxiety, poor comprehension, colorful hallucinations, and auditory hallucinations. The mushrooms containing psilocin are *Panaeolus papilionaceus*, *Panaeolus sphinctrinus*, and *Panaeolus subbalteatus*. The antidote is chlorpromazine. An example of a lampterol-containing mushroom is *Lampteromyces japonicus* [42]. Symptoms of lampterol poisoning include vomiting, diarrhea, and abdominal pain. The symptoms of poisoning with fasciculol-containing mushrooms are vomiting, diarrhea, and nerve paralysis. The mushrooms containing fasciculol are *Naematoloma fasciculare* and *Hypholoma fasciculare*.

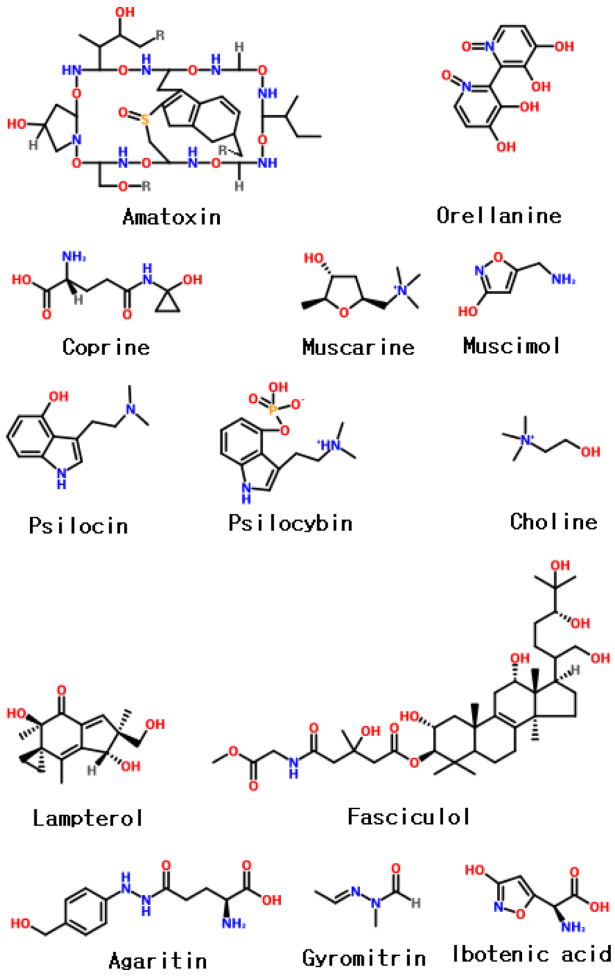

Fig. 1. Chemical structures of various mushroom toxins.

After ingestion, choline in poisonous mushrooms is converted into acetylcholine in the body. Symptoms of choline toxicity include increased blood pressure, decreased heart rate, pupil contraction, increased blood flow, and increased digestive system activity. The mushrooms containing choline are *Rhodophyllus rhodopolius*, *Russula emetic*, and *Lactarius chrysorrheus*. Symptoms of poisoning with glyzicin-containing mushrooms occur 4~5 days after ingestion, and last more than one month. An example glyzicin-containing poisonous mushroom is *Clitocybe acromelalga*. Severe pain in the hands and feet, caused by peripheral neuropathy, lasts for over a month, but is not fatal.

Orellanine is a heat-stable bipyridine N-oxide. The cyclopeptide orellanine is present in *C. orellanus* and *C. speciosissimus* and hence these two mushrooms are

nephrotoxic. The quinone class of compounds may assemble in renal tissue due to the oxidation of orellanine, and covalent binding of biological structures with those quinones may cause cell damage [8]. Orellanine toxicity symptoms may arise 2~20 days after ingestion. Nausea, abdominal pain, and vomiting are symptoms in the early stages of toxicity. Chills, intense thirst, oliguria or polyuria, and probably anuria follow these. It is usually recommended to continue hemodialysis until there are gradual improvements in renal function [43]. It is evident from *in vitro* data that orellanine generates oxygen radicals at the target site through the redox activation of iron and/or redox cycling. It has also been demonstrated with advanced information on cellular systems that protein synthesis can be inhibited by a metabolite of orellanine [35].

CONCLUSION

There are a large number of mushroom poisoning cases reported every year in areas with high mushroom consumption. Insufficient knowledge and misidentification of species are the leading causes of mushroom intoxication. Some species contain hazardous toxins in varying proportions that cause diverse signs and syndromes. Not only toxic mushrooms but also some edible mushrooms contain poisonous compounds and the severity of intoxication is dependent on the amount consumed. Accidental ingestion of mushrooms is difficult to avoid when there is a lack of knowledge and awareness about mushroom poisoning. Accurate recognition of mushrooms is a fundamental step in avoiding toxicity and enabling successful treatment through the rapid detection of intoxication symptoms. Cases of fatal mushroom poisoning have been reported previously; however, the properties of toxins, syndromes, and mechanisms of toxicity have not been summarized. Thus, it is crucial to review information on mushroom toxins and their fatality. Careful experimental and clinical investigations are required to identify the possible side effects of edible and medicinal mushrooms and enable their safe consumption.

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