Chemosphere 176 (2017) 175–182

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Removal of 30 active pharmaceutical ingredients in surface water under long-term artificial UV irradiation

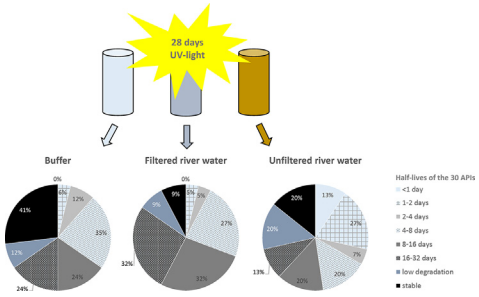
Kristin M. Blum [a], Sara H. Norström [a], Oksana Golovko [b], Roman Grabic [b], Josef D. Järhult [c, d], Olga Koba [b], Hanna Söderström Lindström [a, e, *]

[a] Department of Chemistry, Umeå University, 901 87 Umeå, Sweden
[b] University of South Bohemia in Ceske Budejovice, Faculty of Fisheries and Protection of Waters, South Bohemian Research Center of Aquaculture and Biodiversity of Hydrocenoses, Zatisi 728/II, 389 25 Vodnany, Czech Republic
[c] Section for Infectious Diseases, Department of Medical Sciences, Uppsala University, 751 85 Uppsala, Sweden
[d] Zoonosis Science Center, Department of Medical Biochemistry and Microbiology, Uppsala University, 751 23 Uppsala, Sweden
[e] Department of Public Health and Clinical Medicine, Occupational and Environmental Medicine, Umeå University, 901 87 Umeå, Sweden

HIGHLIGHTS

- Kinetic study on 30 APIs in waters during 28 days of UV irradiation.
- The major removal process was indirect phototransformation.
- The kinetics in natural waters highly depended on the water chemistry.
- Long-term UV-exposure enabled environmental relevant removal kinetics.
- High stability of many APIs studied concerns and emphasizes need for further research.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 December 2016
Received in revised form
9 February 2017
Accepted 11 February 2017
Available online 15 February 2017

Handling Editor: Klaus Kümmerer

Keywords:
Active pharmaceutical ingredients
Oseltamivir
Photostability
Photolysis
Half-lives
Aquatic environments

ABSTRACT

This study investigated the i) kinetics, and ii) proportion of photolysis of 30 relatively stable active pharmaceutical ingredients (APIs) during artificial UV irradiation for 28 d in ammonium acetate buffer, filtered and unfiltered river water. Buffer was included to control removal kinetics under stable pH conditions and without particulate matter. Dark controls were used to determine removal due to other processes than photolysis and calculate the proportion of photolysis of the total removal. The removal of each API in each matrix was determined using online solid phase extraction/liquid chromatography tandem mass spectrometry (online SPE/LC-MS/MS). Most APIs transformed during the 28 d of UV irradiation and the dark controls showed that photolysis was the major removal process for the majority of the APIs studied. The half-lives ranged from 6 h (amitriptyline) in unfiltered river water to 884 h (37 d, carbamazepine) in buffer. In unfiltered river water, the proportion of APIs with short half-lives (<48 h) was much higher (29%) than in the other matrices (4%), probably due to additional organic carbon, which could have promoted indirect photolysis. Furthermore, two APIs, memantine and fluconazole, were stable in all three matrices, while alprazolam was stable in buffer and unfiltered river water and four additional APIs were stable in buffer. Considering the relatively long-term UV-exposure, this study enabled the investigation of environmentally relevant half-lives in natural waters. Many APIs showed

* Corresponding author. Department of Public Health and Clinical Medicine, Occupational and Environmental Medicine, Umeå University, 901 87 Umeå, Sweden.
E-mail address: hanna.soderstrom@umu.se (H. Söderström Lindström).

http://dx.doi.org/10.1016/j.chemosphere.2017.02.063

high persistence, which is environmentally concerning and emphasizes the importance of further studies on their environmental fate and effects.

1. Introduction

Pharmaceuticals and their metabolites are widely distributed in the environment (Ternes, 1998; Kümmerer, 2009a; Verlicchi et al., 2012; Aus der Beek et al., 2015) and have been given high attention for their possible environmental and human effects. Active pharmaceutical ingredients (APIs) are distributed to sewage water, not only from human and animal excretion (Jjemba, 2006; Lienert et al., 2007; Aus der Beek et al., 2015) but also through discarding of unused drugs and the release from production sites (Fick et al., 2009a; Larsson et al., 2007). They end up in surface water mainly through discharge of treated, and in some cases, untreated sewage water (Miege et al., 2009; Verlicchi et al., 2012). Monitored drugs are, for instance, hormones included in contraceptive pills (Larsson et al., 1999; Desbrow et al., 1998), antibiotics (Al Aukidy et al., 2012; Alexy et al., 2006; Hartig et al., 1999; Hirsch et al., 1999; Kümmerer, 2009b), antivirals (Takanami et al., 2010, 2012; Azuma et al., 2015), anti-inflammatory drugs (Heberer, 2002), illicit drugs (Ort et al., 2014; Evgenidou et al., 2015; McCall et al., 2016), and psycholeptics (Ternes, 1998; Heberer, 2002; Calisto and Esteves, 2009; Kosjek et al., 2012; Zuccato et al., 2000). They have mostly been detected in sewage effluent (Larsson et al., 1999; Desbrow et al., 1998; Al Aukidy et al., 2012; Alexy et al., 2006; Hartig et al., 1999; Hirsch et al., 1999; Heberer, 2002) and sludge (Hörsing et al., 2011), as well as surface water (Al Aukidy et al., 2012; Hirsch et al., 1999; Heberer, 2002) but also in ground (Heberer, 2002) and drinking water (Heberer, 2002; Zuccato et al., 2000). Near production plants, several APIs have been detected in surface, ground, and drinking water, and the antibiotic ciprofloxacin was present in non-effluent affected lake water at higher concentration than in the serum of ciprofloxacin-treated patients (Fick et al., 2009b).

Once in the environment APIs can have multiple effects; not only traditionally ecotoxicological and human health effects, but also more specific effects related to their mode of action such as resistance development in bacteria due to antibiotics in the environment (Kümmerer, 2009c). For instance, behavioral effects of the psychiatric drug oxazepam have been shown to impact the aquatic ecosystem (Brodin et al., 2013) and antibiotic resistance genes have been discovered in sewage treatment plant (STP) effluents (Reinthaler et al., 2003), downstream of STPs (Costanzo et al., 2005) and in antibiotic-contaminated river sediment sampled close to drug production facilities (Kristiansson et al., 2011). Since all known resistance mechanisms with clinical importance originate from environmental bacteria, these results suggest selection and mobilization of antibiotic resistance in the environment as one of the driving forces behind antibiotic resistance in humans. Because the antiviral drug oseltamivir's active metabolite oseltamivir carboxylate (OC) has been detected in waterways (Söderström et al., 2009; Takanami et al., 2010) and oseltamivir can induce resistance in influenza viruses in their natural hosts (Järhult et al., 2011), this is a potential public health threat (Järhult, 2012).

Since many APIs have shown resistance during sewage water treatment and the biodegradation process, it is important to study the environmental fate of these compounds and photolysis is one of the most important removal processes (Boreen et al., 2003; Fatta-Kassinos et al., 2011). There are two major photolysis pathways, direct and indirect photolysis. Direct photolysis occurs when a molecule absorbs a photon from a light source that causes the molecule to transform. Indirect photolysis involves naturally occurring substances, for instance organic matter or nitrate, which absorb photons and generate strong reactive species that in turn induce a transformation of the molecule in question (Challis et al., 2014; Yan and Song, 2014). Hence, it is important to consider the chemistry of the medium where the photolysis takes place. Parameters, such as temperature, light intensity and wavelength, pH, organic matter, and turbidity, can influence the pathway and the rate of the photolysis reaction (Boreen et al., 2003; Fatta-Kassinos et al., 2011). However, the parameters used in experiments often vary and are limited described (i.e. the light source, water chemistry). These experimental variations in combination with few APIs included in studies on natural waters and the large chemical diversity of APIs, limit the comparability between studies. Thus, considering a wide range of APIs in one study could improve the ability to compare photostability and kinetics of individual APIs and between anatomical subgroups, respectively.

Phototransformation studies have included a variety of pharmaceuticals and waters previously (Boreen et al., 2003; Fatta-Kassinos et al., 2011; Yan and Song, 2014). To our knowledge, only a few studies on environmental photofate have investigated a large number of pharmaceuticals (>20 APIs) under controlled laboratory conditions (Wang and Lin, 2014) and in field (Hanamoto et al., 2014). Most studies have focused on a few pharmaceuticals (i.e. Andreozzi et al., 2003; Bergheim et al., 2014; Boreen et al., 2003; Fatta-Kassinos et al., 2011; Matamoros et al., 2009). To the best of our knowledge, our study is the first to investigate the photofate of a large variety of relatively stable pharmaceuticals during a long-term laboratory experiment. We aimed to determine i) the kinetics of 30 APIs in surface water and ammonium acetate buffer during 28 d of artificial UV irradiation, and ii) the respective proportion of photolysis of the total removal.

2. Experimental

2.1. Selection of APIs

First, a pre-study was performed with artificial 8 h UV-exposure of 62 APIs that were selected based on consumption and environmental relevance (Fick et al., 2010). The 28 APIs that showed high stability in this pre-study (<10% photolysis) (Table S11 of the Supplementary Material) were selected to be included in our study together with desloratadine, which had a relatively long half-life of 25 d, and oseltamivir carboxylate (OC), a substance of special interest (see Table 1).