Removal of pharmaceuticals by a surface water treatment plant

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ABSTRACT

Several pharmaceuticals were followed through a drinking water production process on the river Meuse. Tramadol and levetiracetam were the most common compounds while cytostatics were not detected. All compounds found at that intake point had an annual consumption greater than 90 mg/inhabitant. The tracer substance 1,2,3-benzotriazole allowed estimation of the maximal concentration of pharmaceuticals and the evolution profile for tramadol and sotalol. After preozonation of raw water, most pharmaceuticals were completely removed, except levetiracetam and irbesartan, confirming the efficiency of this advanced oxidation process. Irbesartan and levetiracetam were completely removed by granular activated carbon filtration. Levetiracetam was the most reluctant compound. A conventional multi-barrier treatment combining ozone and activated carbon, already used for several decades before implementation in wastewater treatment, can completely remove most pharmaceuticals. Therefore, drinking water without any significant health-related amount of these pharmaceuticals can be produced from surface water.

Key words | activated carbon, drinking water, ozone, pharmaceuticals, surface water, water treatment

INTRODUCTION

Many pharmaceuticals have been reported in water (Hughes et al. 2013). It has been shown that untreated or conventionally treated wastewater represents the main pollution stream to the water cycle (Ternes 1998; Petrie et al. 2015). Therefore, surface water is the most impacted natural resource from this cycle (Ternes 1998; Luo et al. 2014).

The fluxes of pharmaceuticals to surface waters are mainly correlated with their consumption, corrected for human excretion, removal by wastewater treatment and dilution in the receiving water (Golet et al. 2002; Buerge et al. 2006). The least metabolized and most reluctant compounds will be discharged to surface water, e.g. carbamazepine, but also pharmaceuticals largely consumed will be found in surface water even when their metabolism and removal are efficient, e.g. ibuprofen. Their physicochemical properties (solubility, polarity, ionization) and persistence in water also determine their presence in surface water. To select the most meaningful pharmaceuticals, all these factors must be taken into account. Nevertheless, a selection based on their usage can already identify the most prominent ones.

Some pharmaceutical categories (hormones, antibiotics, psychotropics, anti-depressants) are of concern for aquatic life, because of low biologically active concentrations. Less biologically active substances can be of concern too when high concentrations are reached. Some pharmaceuticals have been shown to spread along the food chain, such as diclofenac (Green et al. 2016). Therefore, concern for human exposure through the environment has been raised, including drinking water.
Drinking water production by direct abstraction of surface water is mostly realized by a multi-barrier treatment process involving coagulation–flocculation, sedimentation, filtration and disinfection steps. This process has been improved by pre-oxidation with ozone (Kruthof & Masschelein 1999). In Europe, some studies have reported the presence of pharmaceuticals in drinking water produced from groundwater or surface water, usually at concentrations below 0.1 μg/L and sometimes at higher concentrations (Ternes 1998; Benner et al. 2013). Few studies have assessed the removal efficiency of a conventional treatment directly abstracting surface water (Benotti et al. 2009; Vulliet et al. 2009; Huerta-Fontela et al. 2011). The Meuse is an international river providing drinking water to more than 6 million people. Being significantly influenced by wastewaters, pharmaceuticals have been regularly found (Houtman et al. 2013) and an assessment of the drinking water production processes along this river is desirable. Therefore, a study was undertaken to assess the efficiency of removing pharmaceuticals at a surface water treatment plant abstracting directly from the Meuse river.

**EXPERIMENTAL**

**Chemicals and reagents**

Acetonitrile, methanol, formic acid, and water were obtained from Biosolve. Ammonia (28–30%) and sodium thiosulfate (0.1 N) were obtained from Sigma-Aldrich. Ultra-pure water (UP water, 18.2 MΩ·cm) was produced by a Purelab Prima unit (Elga).

Atenolol, bisoprolol, carbamazepine, cyclophosphamide, ifosfamide, irbesartan, levetiracetam, metoprolol, primidone, propranolol, ranitidine, sotalol, sulfamethoxazole, tramadol, trazodone, sotalol-d7, sulfamethoxazole-d4, tramadol-d6, and carbamazepine-d10 were obtained from AccuStandard. Bezafibrate, diclofenac, ibuprofen, and naproxen were obtained from Sigma-Aldrich; 1,2,3-benzotriazole was obtained from Chem-Lab; 1,2,3-benzotriazole-d4, diclofenac-d4, ibuprofen-d3, MCPA-d5, and MCPB-d6 were obtained from A2S. Seven calibration solutions containing each pharmaceutical from 10 ng·L⁻¹ to 200 ng·L⁻¹ and 50 ng·L⁻¹ of the internal standards were prepared weekly in UP water.

Nitrogen gas (96%) was produced by a nitrogen generator from Parker Balston. High-purity argon (6.0) was purchased from Messer and used as collision-induced-dissociation gas (CID gas) in liquid chromatography–tandem mass spectrometry (LC-MS/MS).

**On-line SPE and chromatographic conditions**

On-line solid-phase extraction (SPE) (Combipal 2777 Sample Manager) was performed with an OASIS HLB column (Waters, 30 mm × 2.1 mm, 20 μm) for bezafibrate, diclofenac, ibuprofen, naproxen, 1,2,3-benzotriazole and the associated internal standards. For all other compounds, direct injection of the sample was performed into the high-performance liquid chromatography (HPLC) system. The chromatographic system was a ultra-performance liquid chromatography (UPLC) Acquity (Waters) equipped with a binary gradient pump and a thermostated column compartment. For direct injection, the separation was performed on a UPLC Acquity TSS T3 column (Waters, 150 mm × 2.1 mm, 1.8 μm) at 40 °C using an acetonitrile (0.05% formic acid):water (0.05% formic acid) gradient. For on-line SPE, the chromatographic separation was performed on an Acquity UPLC BEH C18 column (Waters, 100 mm × 2.1 mm, 1.7 μm) at 40 °C using an acetonitrile:water (0.05% ammonia) gradient. For direct injection, the gradient elution was: 0 min water (0.05% formic acid), from 0 to 8.5 min a linear gradient up to acetonitrile (0.05% formic acid):water (0.05% formic acid) (97.5:2.5 v/v) followed by an isocratic step for 2 min. For on-line SPE, the gradient elution was: 0 min acetonitrile:water (0.05% ammonia) (98:2 v/v), from 0 to 6 min a linear gradient up to acetonitrile:water (0.05% ammonia) (35:65 v/v), from 6 to 7.5 min a linear gradient up to 100% acetonitrile followed by an isocratic step for 2 min.

**Mass spectrometry conditions**

The liquid chromatography was coupled to a triple quadrupole mass spectrometer (Xevo TQ-MS, Waters) equipped with an electrospray ionization source operating in negative or positive mode at a vaporizer temperature of 575 °C to 600 °C. Nitrogen was used as desolvation gas (1,000 L·hr⁻¹) and cone gas (50 L·hr⁻¹). For tandem mass spectrometry the deprotonated [M-H]⁻ or the protonated [M + H]⁺ ions were
used as precursor. For most compounds, two transitions were monitored using a dwell time of 5 to 15 milliseconds. One daughter ion was used for confirmation (C) and another for quantification (Q), with an allowed deviation from the expected peak intensity ratio C/Q < 20% to 30%, depending on the substance. Argon was used as a CID gas (0.15 mL.min⁻¹). Mass spectrometry conditions, internal standards used for quantification and limit of quantification (LOQ) of the studied compounds are included in Table 1.

The limit of detection (LOD) was determined by spiking a water sample with the analyte at a concentration close to the limit of detection, and measuring seven times the spiked sample under repeatability conditions. The following equation was used:

\[ LOD = \sqrt{2} \times t(n - 1; \alpha = 0.01) \times \sigma \]

where \( t(n - 1; \alpha = 0.01) \) is the value for \( n \) repetitions from the Student’s table at 99% confidence, and \( \sigma \) is the standard deviation. The limit of quantification (LOQ) was twice LOD.

### Sample collection

Water samples were regularly collected at several monitoring points of the Tailfer treatment plant: 500 mL water was collected in a brown glass bottle with a brown glass stopper and containing 1 mL of sodium thiosulfate. The water samples were stored at 2–5 °C and analyzed within 14 days.

### The Tailfer treatment plant

At the Tailfer treatment plant (VIVAQUA, Brussels, Belgium), usual production was between 120,000 and 160,000 m³/day of drinking water. This plant drew water directly from the river Meuse to produce drinking water by a conventional treatment: pre-ozonation (0.5 to 2 mgL⁻¹ ozone), coagulation–flocculation, sedimentation, first stage filtration (dual-layer with 40 cm sand and 80 cm granular activated carbon TL830 from Chemviron Carbon, Belgium).
10 to 15 minutes contact time), ozonation (0.5 to 1.5 mgL$^{-1}$ ozone), sodium bisulfite injection, second stage filtration (3 m of granular activated carbon F300 from Chemviron Carb, 12 to 20 minutes contact time) and a chlorine injection. Both filtration stages were working in a biological mode. The coagulation–flocculation step was performed at pH 7.0–7.2 by adding sodium silicate and aluminum sulfate. Before chlorine injection, the pH was raised to 8.0.

Samples were taken regularly from the river and the outlet of the pre-ozonation, first stage filtration and second stage filtration.

RESULTS AND DISCUSSION

Pharmaceuticals at the intake point of the Tailfer treatment plant

Before monitoring pharmaceuticals in water, a selection of some representative compounds must be realized among this huge family. Therefore, the global consumed amounts of pharmaceuticals at Belgian levels were used to select some representative compounds. Even if several pharmaceuticals are well removed by wastewater treatment plants and can be adsorbed or biodegraded in surface water, such as ibuprofen (Buser et al. 1999; Wang & Wang 2016), the large amounts used can lead to trace levels in surface waters. For example, the use of ibuprofen at around 50 tons/year, placing this compound in the top five most used pharmaceuticals in Belgium, justifies its selection. Moreover, monitoring data from some international studies confirmed its ubiquitous presence in surface water (Ternes 1998; Buser et al. 1999; Sacher et al. 2008; Hughes et al. 2013; Luo et al. 2014). Several selected pharmaceuticals for this study were sold at more than 2 tons/year. Given a Belgian population of about 11 million people, between 600,000 and 700,000 inhabitants releasing wastewater in the Meuse river upstream of the Tailfer treatment plant (Volz 2010) and a medium river flow at 120 m$^3$.sec$^{-1}$ at the intake point of the treatment plant (minimum river flow = 30 m$^3$.sec$^{-1}$, maximum river flow = 600 m$^3$.sec$^{-1}$), a minimum of 2 tons/year of consumed pharmaceuticals could lead to a concentration of about 30 ng.L$^{-1}$ (between 120 ng.L$^{-1}$ at minimum river flow and 6 ng.L$^{-1}$ at maximum river flow) neglecting any human body metabolization and removal by any biological, physical or chemical process. Therefore, the selected pharmaceuticals represented a consumption of at least 180 mg/inhabitant/year. Pharmaceuticals less-used in Belgium (<2 tons/year) but regularly found in European surface waters were also selected (Ternes 1998; Loos et al. 2009). Two cytostatic drugs already studied in Europe (Buerge et al. 2006), cyclophosphamide and ifosfamide, were also included among the 19 selected compounds, given their high human toxicity (Kümmerer et al. 2016).

Among the pharmaceuticals monitored during the 2 years, ten were quantified above their quantification limit (Table 2). Tramadol reached the highest concentration and was frequently present. Levetiracetam was also frequently quantified, but reached lower concentrations.

The two cytostatic active substances, cyclophosphamide and ifosfamide, were not found in the river Meuse above their quantification limit, nor above their detection limit (Table 2).

Table 2 | Compounds monitored in the river water at the Tailfer treatment plant; '> LOQ' represents the relative number of samples higher than LOQ (%); 'Cmax' represents the highest concentration measured (μg.L$^{-1}$)

<table>
<thead>
<tr>
<th>Compound</th>
<th>&gt; LOQ</th>
<th>Cmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3-benzotriazole</td>
<td>100</td>
<td>0.146</td>
</tr>
<tr>
<td>Atenolol</td>
<td>4</td>
<td>0.010</td>
</tr>
<tr>
<td>Bezafibrate</td>
<td>0</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Bisoprolol</td>
<td>0</td>
<td>&lt;0.010</td>
</tr>
<tr>
<td>Carbamazepine</td>
<td>27</td>
<td>0.031</td>
</tr>
<tr>
<td>Cyclophosphamide</td>
<td>0</td>
<td>&lt;0.023</td>
</tr>
<tr>
<td>Diclofenac</td>
<td>31</td>
<td>0.052</td>
</tr>
<tr>
<td>Ibuprofen</td>
<td>35</td>
<td>0.020</td>
</tr>
<tr>
<td>Ifosfamide</td>
<td>0</td>
<td>&lt;0.022</td>
</tr>
<tr>
<td>Irbesartan</td>
<td>31</td>
<td>0.033</td>
</tr>
<tr>
<td>Levetiracetam</td>
<td>92</td>
<td>0.033</td>
</tr>
<tr>
<td>Metoprolol</td>
<td>0</td>
<td>&lt;0.007</td>
</tr>
<tr>
<td>Naproxen</td>
<td>35</td>
<td>0.022</td>
</tr>
<tr>
<td>Primidone</td>
<td>0</td>
<td>&lt;0.016</td>
</tr>
<tr>
<td>Propanolol</td>
<td>0</td>
<td>&lt;0.015</td>
</tr>
<tr>
<td>Ranitidine</td>
<td>2</td>
<td>0.027</td>
</tr>
<tr>
<td>Sotalol</td>
<td>39</td>
<td>0.038</td>
</tr>
<tr>
<td>Sulfamethoxazole</td>
<td>0</td>
<td>&lt;0.020</td>
</tr>
<tr>
<td>Tramadol</td>
<td>92</td>
<td>0.067</td>
</tr>
<tr>
<td>Trazodone</td>
<td>0</td>
<td>&lt;0.020</td>
</tr>
</tbody>
</table>
limit (Table 2). As their use was lower than 10 mg/inhabitant/year, it is not expected to find these compounds in a high flow river such as the Meuse. Therefore, based on consumption data it can be expected that other cytostatic drugs will not be found in this surface water at a concentration higher than 10 ng.L⁻¹, such as capecitabine and 5-fluorouracil. These toxic pharmaceutical compounds would not represent a threat to human health through drinking water in this watershed.

Among the other pharmaceuticals, all quantified compounds represented a consumption larger than 90 mg/inhabitant/year. Metoprolol and propranolol were not detected despite a consumption greater than this threshold. Among the beta-blockers, these two more lipophilic compounds are known to be eliminated mostly by liver metabolism (by dealkylation, side-chain oxidation, ring hydroxylation), compared with more hydrophilic compounds such as atenolol and sotalol, which are almost exclusively excreted unchanged in urine (Mehvar & Brocks 2004). For these reasons, the absence of metoprolol and propranolol in the river Meuse at that intake point was not astonishing.

The ubiquitous polar chemical 1,2,3-benzotriazole, mostly used as a corrosion inhibitor and also as an anti-freeze fluid and found at high concentration in wastewaters and surface waters (Giger et al. 2006; Weiss et al. 2006), was also monitored. The concentration of 1,2,3-benzotriazole in the river Meuse at the intake point of the Tailfer treatment plant was always higher than any of the pharmaceuticals followed. For two pharmaceutical compounds, tramadol and sotalol, a close and similar concentration evolution was observed to 1,2,3-benzotriazole (Figure 1). This could be ascribed to a regular consumption and release of both tramadol and sotalol through wastewater to the river, similarly to the regular use of benzotriazole in many fields. Therefore, this polar corrosion inhibitor could be used as a tracer to estimate (by overestimation) the evolution of usual- and high-consumption pharmaceuticals. One exception could be the anti-diabetic drug metformin, which was shown to be present in the river Meuse at higher concentrations but was not considered in this study (Houtman et al. 2013).

The highest concentrations were achieved from May to November, when the river’s flow was the lowest. When the flow increased significantly after a heavy rainfall, the concentration of the pharmaceuticals decreased while their amount released to the river was higher (unpublished results). Increased release of chemicals due to heavy rainfalls can be ascribed to several transport phenomena, such as the runoff of soil- or sludge-adsorbed chemicals or the decreased removal efficiency at wastewater treatment plants because of a reduced hydraulic residence time. Since the studied pharmaceuticals are expected to be weakly adsorbed, we believe that a decreased hydraulic residence time at wastewater
treatment plants would increase their release into the river (Kreuzinger et al. 2004), but their concentration would decrease due to a stronger dilution effect of the rainfall.

**Removal of pharmaceuticals at the Tailfer treatment plant**

The pharmaceuticals were followed along the process of the Tailfer treatment plant, at pre-ozonation, first stage filtration (sand/activated carbon), and second stage filtration (activated carbon). These stages were selected for their known removal efficiency of pharmaceuticals, while coagulation–floculation has been demonstrated to be inefficient towards these polar compounds (Ternes et al. 2002).

Most pharmaceuticals found in raw river water were completely removed at the first stage of the treatment process (<LOD), the pre-ozonation step, with the only exceptions of irbesartan and levetiracetam. At this pre-ozonation step, ozone was quickly decomposed to the hydroxyl radical due to the high organic matter content of raw surface water (Hoigné & Bader 1979), leading to an advanced oxidation process (AOP) combining molecular ozone and the hydroxyl radical, both known to react with many pharmaceuticals (Ternes et al. 2003). The great reactivity of many pharmaceuticals with molecular ozone and the hydroxyl radical can be ascribed to the presence of sulfide and amine groups, double-bonds and electron-rich aromatic rings. The efficiency of this AOP process was confirmed by observing atrazine partial elimination at this treatment step, before the year 2006 when this herbicide was still observed in the river Meuse (unpublished results). Therefore, the pre-ozonation step applied to produce drinking water from surface water is an AOP process similar to the recently studied and proposed post-ozonation step for wastewater (Hollender et al. 2009), this pre-ozonation for drinking water production having been already implemented for more than 25 years at several European drinking water production plants (Kruithof & Masschelein 1999).

After the pre-ozonation step, the removal of irbesartan and levetiracetam reached 40–50% and 5–40% respectively. These removals were only calculated for samples containing these pharmaceuticals above their limit of quantification (LOQ) after pre-ozonation. Because of the aliphatic structure of levetiracetam, this compound is not expected to be oxidized by molecular ozone or the hydroxyl radical. After the first stage filtration, irbesartan was completely removed while levetiracetam was sometimes still observed, with a removal limited to 35–50%. After the second stage filtration, the removal of levetiracetam was complete. The ozonation step inbetween the two filtration steps was not monitored since this step was designed for disinfection of bacteria and viruses, and therefore was not generating enough hydroxyl radicals to be an efficient AOP process. As all pharmaceuticals easily oxidized by molecular ozone were already removed at the pre-ozonation step (not the case for levetiracetam and irbesartan), there was no incentive to follow them at the ozone step.

Some studies have considered the efficiency of water treatment steps for pharmaceuticals (Benotti et al. 2009; Vulliet et al. 2009; Huerta-Fontela et al. 2011). Traces of pharmaceuticals were still found after multi-barrier surface water treatment processes. Benotti et al. (2009) found carbamazepine, sotalol and atenolol in treated water when using chlorine oxidation, but not with ozone. Only two pharmaceuticals resistant to ozone were found in treated water, but ozone removed more pharmaceuticals compared with chlorine. Huerta-Fontela et al. (2011) confirmed the resistance of some pharmaceuticals to chlorine oxidation, but also to ozonation for atenolol and sotalol. On the other hand, Vulliet et al. (2009) concluded that most treatments could not completely remove pharmaceuticals from surface water, even for carbamazepine and atenolol when using ozone and activated carbon. In our study, most pharmaceuticals, and especially carbamazepine, atenolol and sotalol, were completely degraded by the pre-ozonation step applied to surface water, confirming that ozone in an AOP process is a stronger and more efficient chemical for oxidizing pharmaceuticals. Therefore, the ozone oxidation of raw surface water proved to be very efficient for producing drinking water free of pharmaceuticals.

For irbesartan, studies also reported incomplete elimination by ozone, with removals from 51% to 65% for wastewater and surface water treatments, similarly to our study (Huerta-Fontela et al. 2011; Kovalova et al. 2013). Compared with irbesartan, the complete removal of losartan was referred to activation of its 1,3-diazole aromatic ring by the chlorine substituant (Huerta-Fontela et al. 2011). As chlorine is an electron-withdrawing group, the reactivity...
towards ozone should be reduced by this kind of substituant. Another explanation would be the faster oxidation kinetic with ozone for the more electron-rich imidazole ring of losartan, compared with the less reactive and more sterically hindered imidazolinone ring of irbesartan.

Levetiracetam presented the highest resistance to the combination of ozone and granular activated carbon (GAC). Few studies have reported the removal of this compound with ozone or activated carbon (Kovalova et al. 2013; Margot et al. 2013) and they were mainly focused on wastewaters and powdered activated carbon. In wastewaters, ozonation of levetiracetam reached between 18% and 54% removal, in line with our results at the pre-ozonation step. This pre-ozonation is an AOP process with efficiencies close to the ozonation of wastewater effluents. Activated carbon adsorption reached between 64% and 97% removal for levetiracetam with powdered activated carbon applied to wastewater effluents. In our study, lower removals were achieved after the first stage filtration (only 80 cm of GAC), since powdered activated carbon is more efficient than GAC. Higher and complete removal for levetiracetam was therefore achieved after the second CAG filtration step. Implementation of a final CAG filtration step after the ozone disinfection step allows also the removal of more precursors of halogenated disinfection by-products in the case of chlorine final disinfection and the reduction of bacterial regrowth in distribution networks. Therefore, a drinking water production plant designed to produce more biologically stable water can also efficiently reduce micropollutants like pharmaceuticals. These compounds have been monitored for more than 5 years along this treatment process and have never been detected in the produced drinking water, showing the robustness of these combined steps whatever the pollution of the river.

**Evaluation of human health impact of pharmaceuticals through drinking water**

The human health risk of pharmaceuticals through drinking water has been evaluated and traces of pharmaceuticals in drinking water are not considered as a human health risk (Bruce et al. 2010; WHO 2013a). Moreover, according to the TTC concept (Threshold of Toxicological Concern), non-genotoxic chemicals would have a safe ingestion dose at 18 μg/day (Kroes et al. 2004), corresponding to a safe drinking water threshold of 1.8 μg.L⁻¹, considering a daily consumption of two litres and a source contribution of 20% (WHO 2013b). As pharmaceuticals should be ingested more by water than by food consumption, the source contribution for drinking water should be higher, increasing therefore the safe drinking water threshold. For genotoxic pharmaceuticals, the same evaluation leads to 0.015 μg.L⁻¹ for drinking water, considering a safe intake dose at 0.15 μg/day. As all pharmaceuticals in this study were below their LOQ after the treatment plant, no human health impact is expected through consumption of drinking water. This health risk evaluation does not take into account the mixture effect of several pharmaceuticals, but a relevant mixture effect implies that all compounds share the same endpoint and mode of action. From this study, this can be considered for beta-blockers (atenolol, bisoprolol, metoprolol, propranolol, sotalol) but no relevant mixture effect is expected in drinking water since their complete removal was therefore the safe drinking water threshold. For genotoxic pharmaceuticals, the same evaluation leads to 0.015 μg.L⁻¹ for drinking water, considering a safe intake dose at 0.15 μg/day. As all pharmaceuticals in this study were below their LOQ after the treatment plant, no human health impact is expected through consumption of drinking water. This health risk evaluation does not take into account the mixture effect of several pharmaceuticals, but a relevant mixture effect implies that all compounds share the same endpoint and mode of action. From this study, this can be considered for beta-blockers (atenolol, bisoprolol, metoprolol, propranolol, sotalol) but no relevant mixture effect is expected in drinking water since their complete removal by the drinking water production process was shown.

**CONCLUSION**

Some pharmaceuticals were found in the river Meuse at the intake point of a drinking water production plant, at concentrations less than 0.07 μg.L⁻¹. These compounds were associated with a human consumption greater than 90 mg/inhabitant/year. Tramadol and levetiracetam were the most frequently quantified compounds in this river, while cytostatic active substances were not detected. The polar chemical 1,2,3-benzotriazole allowed the estimation of the maximal concentration of the monitored pharmaceuticals and also the evolution profile of tramadol and sotalol.

At the Tailfer treatment plant, most of these compounds were completely removed after the first ozonation step of the raw surface water, with the exception of levetiracetam and irbesartan. Their partial removal confirmed that this first ozonation step can be considered as an advanced oxidation process. Irbesartan was then completely removed by the following granular activated carbon filtration. Levetiracetam appeared to be the most reluctant compound for this water treatment, but was completely removed after a second granular activated carbon filtration. The multi-barrier treatment
composed of ozone oxidation and granular activated carbon was able to remove the monitored Pharmaceuticals. Therefore, it was shown that this conventional water treatment process can produce drinking water without any significant health-related amount of these pharmaceuticals.

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