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ELIMINATION OF HUMAN PHARMACEUTICALS BY YELLOW WATER OZONATION

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ABSTRACT

Separate collection of urine (yellow water) as well as feces is a potential measure to protect water bodies from pollution with human pharmaceuticals. In this study the removal of four pharmaceuticals (carbamazepine, diclofenac, ibuprofen, clofibric acid) by batch ozonation from non-concentrated and from threefold freeze-concentrated yellow water, both spiked with the pharmaceuticals in concentrations of 10 mg/l, was investigated at different pH. Pharmaceuticals were analysed by solid phase extraction (SPE) and gas chromatography with flame ionisation detection (GC/FID). While diclofenac and carbamazepine were less efficiently removed under alkaline conditions than in the neutral range, this pH influence was not observed with clofibric acid and ibuprofen. Pharmaceutical elimination by ozonation was lower in yellow water freeze concentrates due to the more concentrated organic matrix. Compared to literature data about ozonation of secondary effluents, the ozonation of diverted yellow water for pharmaceutical removal cannot be considered as economically feasible.

KEYWORDS: ecological sanitation, ozonation, pharmaceuticals, urine

INTRODUCTION

In the conventional sanitation system (discharge of domestic wastewater to sewers with subsequent centralised treatment in municipal wastewater treatment plants), mainly human excreta contribute to the pollution of surface water bodies (Goebel et al. 2005; Ternes 1998) and aquifers (Kreuzinger et al. 2004) with human pharmaceuticals. While acute toxicity of pharmaceuticals toward aquatic organisms is observed in the 1 to 1000 mg/l range (Webb 2004), chronic toxicity of these substances is reported to be in the $\mu\text{g/l}$ range (Triebkorn et al. 2004), i.e. a range which is close to levels detected in surface waters (Ternes 1998). Ecological sanitation (Otterpohl et al. 2003) is a means to block this pathway as human excreta are not discharged to the municipal wastewater in this sanitation scheme, but are used after proper treatment as fertilizer and soil conditioner. Because carbamazepine, diclofenac, ibuprofen and clofibric acid (initial concentration 10 mg/l) were not eliminated during a one year storage period of yellow water (Gajurel et al. 2007), application of yellow water as organic fertilizer in agriculture is a potential pathway of urine-borne human pharmaceuticals into crops and groundwater and can only be recommended if environmental safety is ensured.

As several pharmaceuticals have been shown to be efficiently removed from secondary effluents with ozone doses of up to 15 mg/l (Ternes et al. 2003), in this study the feasibility of yellow water ozonation for pharmaceutical removal was investigated. Four pharmaceuticals were selected for yellow water spiking which had been detected in groundwater: carbamazepine (CZ) (Kreuzinger et al. 2004), diclofenac (DCF), ibuprofen (IBU), and clofibric acid (CFA) (Heberer et al. 1997). For CZ, an excretion rate with urine of 2-3 % of the orally ingested dose and a daily defined dose of 1 g is reported by Huschek et al. (2004). Considering 1.25 l of urine excreted per capita and day (Udert et al. 2006), a CZ concentration of 16 to 24 mg/l can be calculated in the yellow water of a person under respective medication. Therefore, a spiking concentration of 10 mg/l has been chosen for each of the 4 pharmaceuticals as "worst case" concentrations, i.e. concentrations in urine collected from a small community with members under medication.

MATERIALS AND METHODS

Ozonation experiments. Urine was collected from healthy individuals without any medication. The sampled yellow water (10 l) was combined, spiked with CZ, DCF, IBU, and CFA (10 mg/l each) and stirred until used for ozonation experiments (at least over night). Moreover, threefold freeze concentrates of yellow water from the same individuals were prepared in a batch stirred vessel freeze concentrator at -16°C following the procedure of Gulyas et al. (2004). Portions of 3.5 l of combined freeze concentrates were spiked with pharmaceuticals in the same way.

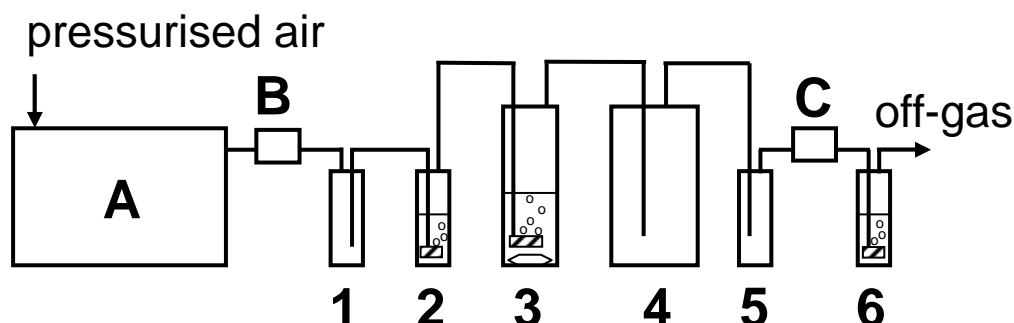


Figure 1 – Experimental set-up for ozonation of yellow water (A: ozone generator; B, C: ozone gas analysers; 1, 5: empty wash bottles; 2: wash bottle with deionised water; 3: reactor; 4: 5-l-bottle for foam-trapping; 6: wash bottle with aqueous 2 g/l $\text{Na}_2\text{S}_2\text{O}_3$ solution for ozone destruction)

Volumes of 1 l of the spiked liquids were transferred to the ozonation reactor (3 in figure 1; ozone concentration in feed gas: 20 to 27 mg/l; feed gas volume flow: 73 l/h; stirring rate 250 min^{-1}) and pH was

adjusted prior to ozonation to 4, 7, and 10 by addition of concentrated sulfuric acid or 32 % NaOH solution. Ozone was generated from air by a Sander laboratory ozoniser (A) and ozone concentrations in feed and off-gas were analysed by ozone analyzers B and C (BMT 961). From the reactor, 6 ml of liquid samples were taken before ozonation and hourly during the experiments each lasting 6 hours. Prior to sampling, the ozone generator was switched off for 5 min, but ozone-free air was continued to bubble into the reactor in order to obtain samples not containing any ozone. Absorbed ozone doses were calculated from mean differences of ozone concentrations in feed and off-gas, gas volume flow, ozonation time between two sampling events (55 min), and liquid volume in reactor.

Analysis. Liquid samples were divided. The pH of one part was adjusted to 6 by mixing 2.5 ml sample with 2.5 ml of a tenfold concentrated Soerensen pH 6 phosphate buffer, the second part was acidified to pH 2 by adding 40 μ l of 85 % phosphoric acid to 2.5 ml sample. Each mixture was thoroughly mixed with 50 μ l of a surrogate standard solution (20 mg of 10,11-dihydrocarbamazepine in 50 ml of acetone). Defined volumes of these mixtures (pH 6: 4 ml; acidified: 2 ml) were subdued to solid phase extraction (SPE) using 60 mg abselutNEXUS cartridges (Varian). Subsequently, each cartridge was rinsed with 1 ml water and finally dried with air. Elution was accomplished with 1 ml methanol into a vial, and the eluate was dried completely in vacuum. The residue was re-dissolved in 50 μ l methanol and vigorously mixed with 40 μ l of the methylation agent trimethylsulfonium hydroxide (TMSH, 0.2 M in methanol; Macherey-Nagel). These solutions were subdued to gaschromatographic analyses with flame ionisation detection (GC/FID; Perkin Elmer Autosystem; split/splitless injector: 260°C; column: 30 m DB5ms, Varian, inner diameter 250 μ m, film thickness 0.25 μ m; carrier gas: N₂, 1 ml/min; temperature programme: 3 min 50°C, 10°/min, 10 min 300°C; detector: 310°C). Quantification of pharmaceuticals was accomplished by measuring standard solutions (2, 5, and 10 mg/l CZ, DCF, IBU, and CFA) generated in the following way: 10 ml of non-spiked urine, resp. yellow water freeze concentrate, were mixed with 20 μ l of methanol solutions containing 1, 2.5, or 5 g/l CZ, DCF, IBU and CFA. These standard solutions were pH-adjusted, mixed with surrogate standard and subdued to SPE as described above. Additionally, blanks (urine or concentrate without any pharmaceuticals) were analysed by GC/FID subsequent to pH adjustment, surrogate standard addition and SPE. Pharmaceuticals were identified by retention indices (ratio of retention time to retention time of surrogate standard) and quantified by ratios of their peak areas to surrogate standard peak areas.

RESULTS AND DISCUSSION

In figure 2, the removal of two different pharmaceuticals from non-concentrated as well as from concentrated yellow water by ozonation at neutral pH is exemplarily displayed: DCF as a substance readily removed by ozonation and CFA requiring very high ozone doses. The data suggest that the elimination rates in the concentrate were slightly lower than in the original urine which can be explained by enhanced competition of organic yellow water constituents with the respective pharmaceuticals for ozone molecules.

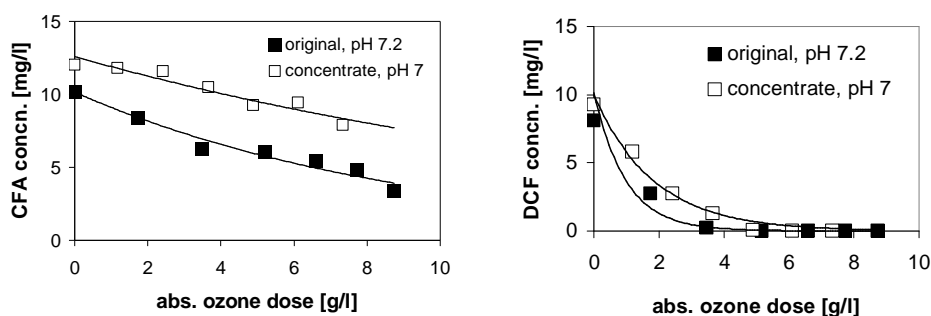


Figure 2. Elimination of CFA (left) and DCF (right) from non-concentrated yellow water (black squares) and from urine threefold enriched by freeze concentration (open squares) as a function of absorbed ozone dose; concentrations are means of two GC/FID analyses (SPE at pH 6 and pH 2)

The elimination of pharmaceuticals by ozonation as displayed in figure 2 was assumed to follow exponential curves. In order to analyse influence of yellow water pH and concentration of yellow water matrix on ozonation, linear regressions have been calculated:

$$\ln c = \ln c_0 - k_D \cdot D_{O_3} \quad (1)$$

with the absorbed ozone dose, D_{O_3} , the initial concentration of the pharmaceutical, c_0 , and the concentration of the pharmaceutical, c , corresponding to the resp. absorbed ozone dose. For determining k_D values for the different pharmaceuticals and ozonation conditions, only pharmaceutical concentrations above twofold limit of detection were utilised (0.3 to 3.1 mg/l with respect to substance and pH for SPE, except CFA by SPE at pH 2: 9.4 mg/l). The determined constants k_D are no rate constants, but are additionally affected by the yellow water matrix: competition of urine organics and hydroxide anions with pharmaceuticals for ozone, scavenging of formed hydroxyl radicals by carbon dioxide species and other radical scavengers. Nevertheless, the constants k_D determined in this study (figure 3) under neutral conditions reflect the rate constants for reactions of ozone with the four investigated pharmaceuticals given by Huber et al. (2005): DCF ($10^6 \text{ M}^{-1}\text{s}^{-1}$) > CZ ($3 \cdot 10^5 \text{ M}^{-1}\text{s}^{-1}$) > CFA ($< 20 \text{ M}^{-1}\text{s}^{-1}$) \approx IBU ($9 \text{ M}^{-1}\text{s}^{-1}$). Rate constants for the reactions with hydroxyl radicals are not largely differing for the four tested pharmaceuticals: $4.7 \cdot 10^9$ (CFA) to $8.8 \cdot 10^9 \text{ M}^{-1}\text{s}^{-1}$ (CZ) (Huber et al. 2005). As already assumed from data shown in figure 2, removal of pharmaceuticals from urine concentrates required more ozone than from non-concentrated yellow water. This is indicated by lower constants k_D for the concentrates (figure 3).

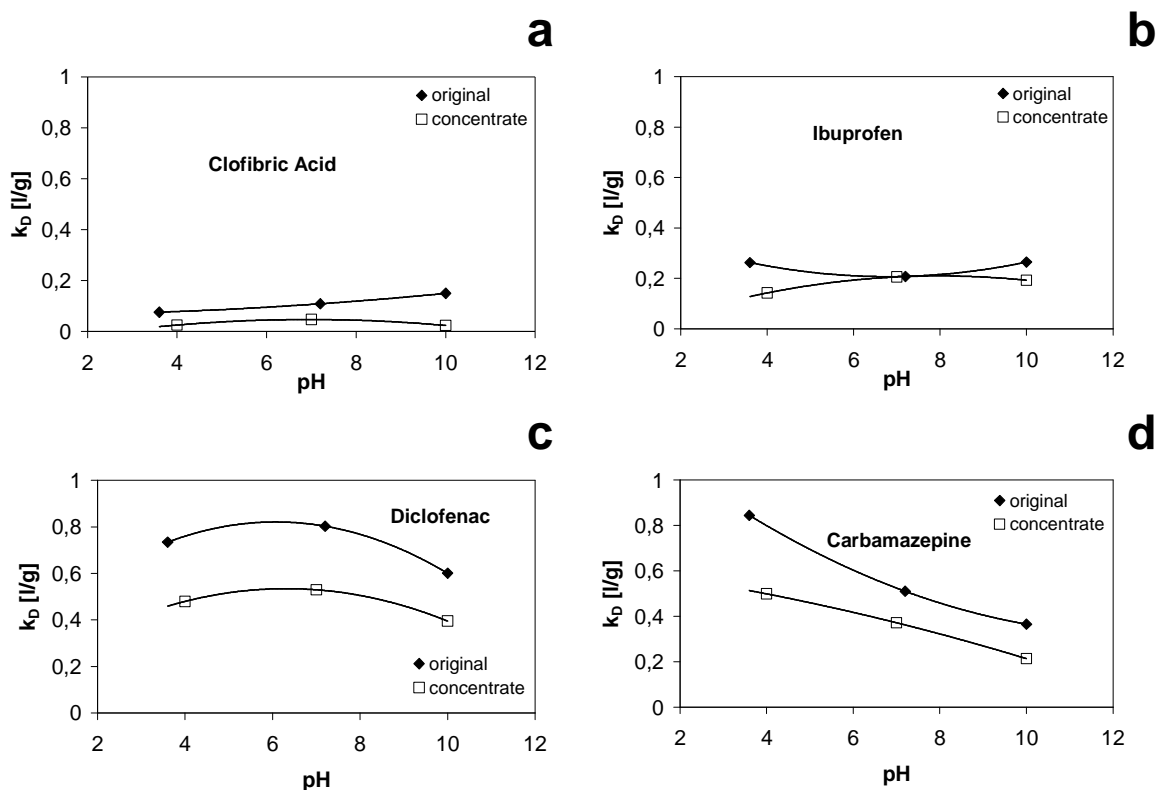


Figure 3. Constants k_D obtained by linear regression according to eq. 1 for removal of the investigated pharmaceuticals by ozonation of non-concentrated (“original”) and freeze-concentrated (“concentrate”) yellow water at different pH

The decreased k_D values for DCF and CZ removal under alkaline conditions (figure 3c, d) can be explained by the fact that enhanced concentrations of hydroxide anions additionally consume ozone leading to the formation of hydroxyl radicals. Although the OH radicals are - like ozone itself - capable to attack pharmaceuticals, they are subject to a more pronounced competition by organic urine constituents which are no pharmaceuticals. The reason is that OH radicals react in a rather non-specific way with C-H bonds (which might be present in urine



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to a higher extent than aromatic and other C-C double bond systems). That this pH effect was not detected for CFA and IBU might be a consequence of their relatively small reaction rates with ozone.

The negligible extent of direct attack of ozone to CFA and IBU is also reflected by the results of an ozonation experiment with the solution of the four pharmaceuticals in deionised water (data not shown): The ratios $k_{D\text{deion.H}_2\text{O}}/k_{D\text{urinepH7}}$ were about 34 and 42 for IBU and CFA, resp., while they were only 1.7 and 4.2 for DCF and CZ, resp. So, it can be assumed that CFA and IBU are predominantly attacked by OH radicals which are scavenged to a high degree in the urine matrix, but not in the deionised water matrix. For DCF and CZ these effects in the urine matrix are not as pronounced, because they are transformed faster by direct reactions with ozone than CFA and IBU.

In spite of a higher efficiency of acidic and neutral than of alkaline conditions for the removal of DCF and CZ from yellow water by ozonation, it has to be considered that urine becomes alkaline after a couple of days storage time due to ureolysis and that lowering of pH consumes substantial amounts of acid because of the high alkalinity of stored urine. Moreover, ozonation at low pH can lead to the formation of chlorinated organics if high concentrations of inorganic chloride anions are present (Rudolph 1993) like in urine.

Table 1 – Comparison of ozonation of alkaline urine and secondary municipal effluents for removal of the four investigated pharmaceuticals

Ozonation of:	Yellow Water				Secondary Effluents			
	(this study)				(literature data)			
Volume to be annually treated [m ³ /a]	39.2 · 10 ⁶ (based on 1.25 l urine excreted per capita and day ^{a)} ; rounded to 0.5 m ³ /(cap·a))				10.5 · 10 ⁹ (entire wastewater processed in German municipal treatment plants in 2001, including domestic and industrial wastewater, infiltration water, stormwater) ^{b)}			
Population served	78.4 · 10 ⁶				78.4 · 10 ^{6 c)}			
Pharmaceutical	CZ	DCF	IBU	CFA	CZ	DCF	IBU	CFA
Elimination rate by ozonation [%]	95	95	50	50	> 98 ^{d)}	> 96 ^{d)}	48 ^{d)}	50 ^{d)}
Required ozone dose to achieve this target [mg/l]	8,190 ^{e)}	5,000 ^{e)}	2,600 ^{e)}	4,600 ^{e)}	5 ^{d)}	5 ^{d)}	5 ^{d)}	5 ^{d)}
Annually required mass of ozone per capita to achieve this goal [kg/(cap·a)]	4.1	2.5	1.3	2.3	0.67	0.67	0.67	0.67
Annually required specific energy ^{f)} [kWh/(cap·a)]	61.5	37.5	19.5	34.5	10.1	10.1	10.1	10.1

^{a)} Udert et al. (2006)

^{b)} Brenk et al. (2006)

^{c)} based on 95 % of German population having access to public sewage^{b)}

^{d)} Ternes et al. (2003)

^{e)} calculated according to eq. 1 using k_D determined for non-concentrated urine at pH 10, see figure 2

^{f)} specific energy required for ozone generation: 15 kWh/kg O₃

Therefore, constants k_D for non-concentrated yellow water ozonation at alkaline pH were selected to estimate specific energy consumption for pharmaceutical removal by this process (Table 1). For this purpose, similar elimination rates for the four investigated pharmaceuticals have been selected as achieved by ozonation of



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secondary effluents in the study of Ternes et al. (2003). Required ozone doses for yellow water treatment, D_{O_3} , were calculated according to eq. 1. From these doses and a volume of urine excreted by an individual within a year of about 0.5 m^3 , the annual ozone mass related to population and finally the specific energy consumption were calculated (Table 1, left part). Analogous data for secondary effluent ozonation were calculated on the base of an ozone dose of 5 mg/l applied by Ternes et al. (2003) taking into account the entire volume of municipal wastewater treated in German public municipal treatment plants in 2001, the German population number, and 95 % of the population having access to public sewage (Table 1, right part). The comparison indicates that yellow water ozonation requires more than six times more energy (based on the CZ data) to remove the same amount of pharmaceuticals than ozonation of secondary effluents in spite of the tremendously higher volume of effluents to be treated. The reason is that secondary effluents contain by two orders of magnitude lower concentrations of organics competing with pharmaceuticals for ozone. Thus, it would be interesting to investigate the ozonation process for pharmaceutical removal from blackwater treated in a membrane-bioreactor within the so-called "blackwater cycle", i.e. in a sanitation scheme utilising treated blackwater for toilet-flushing (Otterpohl et al. 2003).

Ozonation of yellow water cannot be looked at as economically feasible considering more than $60 \text{ kWh}/(\text{cap}\cdot\text{a})$ required for a 95 % removal of CZ. Even saving energy for aeration in the nitrification stage of municipal wastewater treatment plants (if no more ammonia derived from urea in yellow water would be discharged to the sewer in ecological sanitation schemes) does not justify this, because abandoning nitrification in public treatment works would only lead to a reduction in specific energy consumption of about $6 \text{ kWh}/(\text{cap}\cdot\text{a})$ by avoiding about 50 % of aeration (Gulyas et al. 2004). Additionally, ozonation equipment in decentralised Ecosan concepts would require larger investment costs than centralised ozonation plants on municipal level.

CONCLUSIONS

- The investigated pharmaceuticals can be eliminated from diverted yellow water by ozonation.
- For yellow water ozonation alkaline conditions are recommended in order to avoid addition of large amounts of acid and to prevent formation of halogenated organics.
- However, the removal of 95 % of carbamazepine and diclofenac from alkaline urine would require about 4 kg and 2.5 kg of ozone per capita and year, resp.
- For ibuprofen and clofibric acid, even higher amounts of ozone are necessary to achieve a 95 % removal.
- Ozonation of separately collected urine consumes about six times of the energy required for the same removal rate of carbamazepine by ozonation of secondary municipal effluents and is not considered to be economically feasible.

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