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Abstract Bisphenol A (BPA) and nonylphenols (NP) are of major concern to public health due to their high potential for human exposure and to their demonstrated toxicity (endocrine disruptor effect). A limited number of studies have shown that BPA and NP are present in drinking water. The chlorinated derivatives that may be formed during the chlorination step in drinking water treatment plants (DWTP) exhibit a higher level of estrogenic activity than their parent compounds. The aim of this study was to investigate BPA, 353NP, and their chlorinated derivative concentrations using an accurate and reproducible method of quantification. This method was applied to both surface and treated water samples from eight French DWTPs producing from surface water. Solid-phase extraction followed by liquid chromatography–tandem mass spectrometry was developed in order to quantify target compounds from water samples. The limits of detection ranged from 0.3 to 2.3 ng/L for BPA and chlorinated BPA and from 1.4 to 63.0 ng/L for 353NP and chlorinated 353NP. BPA and 353NP were found in most analyzed water samples, at a level ranging from 2.0 to 29.7 ng/L and from 0 to 124.9 ng/L, respectively. In most of DWTPs a decrease of BPA and 353NP was observed between surface water and treated water (36.6 to 78.9 % and 2.2 to 100.0 % for BPA and 353NP, respectively). Neither chlorinated BPA nor chlorinated 353NP was detected. Even though BPA and 353NP have been largely removed in the DWTPs studied, they have not been completely eliminated, and drinking water may consequently remain a source of human exposure.

Keywords Bisphenol A · 353-nonylphenol · Chlorinated derivatives · Drinking water treatment · LC-MS-MS · Water analysis

Introduction

A wide variety of identified man-made chemicals have been found to disrupt the endocrine systems of life forms such as fish, wildlife, and human beings. And yet, the endocrine-disrupting phenolic compounds bisphenol A (BPA) and nonylphenol (NP) are widely used in industry. BPA plays a role in the production of epoxy-resins and polycarbonate plastics, and is also employed as a stabilizer or antioxidant in many types of plastics, such as the polyvinylchloride used for water pipes. Nonylphenols (technical mixture) serve as plastic additives and antioxidants. Moreover, nonylphenol ethoxylates (NPEOs) are widely used as surfactants, in domestic detergents, in pesticide formulations, and in
industrial settings (Katase et al. 2008), producing NP, as a by-product, in the environment (Soares et al. 2008). Moreover, BPA and NP are continuously introduced into the aquatic environment by means of industrial, agricultural, and municipal effluents. More specifically, BPA has been detected in sediments, sewage, soil, water samples... (Vandenberg et al. 2007). In a comparable way, nonylphenols are found throughout the environment, particularly in water resources (Soares et al. 2008).

BPA and NP are of major concern to environmental public health due to their high potential for human exposure and their demonstrated toxicity (European Union 1997; Kang et al. 2006). Humans are exposed to BPA in the food they eat, in the water they drink, and in much of the work they do... Occupational exposure to BPA and NP could potentially occur, especially during their manufacture (NTP 2008). Numerous studies have focused on possible BPA exposure from dietary sources (Vandenberg et al. 2007). Occurrences of BPA and NP have been widely reported in surface water (Voutsa et al. 2006). In addition, some studies have shown BPA to be present in drinking water (Li et al. 2010; Stavrakakis et al. 2008). These authors also reported on the presence of these molecules in corresponding surface water; in yet another study, NP has been detected in drinking water (Soares et al. 2008).

BPA and NP toxicity have been extensively investigated over the past decade. Extensive literature has shown adverse effects on animals following exposure to even a low dose of BPA, including developmental and reproductive toxicity, altered body weight, cancers, and abnormally early puberty (Vandenberg et al. 2010). In addition, epidemiological studies have suggested that human exposure to BPA may be associated with disorders as wide ranging as abnormal karyotype, polycystic ovarian syndrome, obesity, endometrial hyperplasia, recurrent miscarriages, prostate and breast cancer, infertility, attention-deficit hyperactivity disorder, and infertility (Vandenberg et al. 2007). In animals, nonylphenol induces reproductive and developmental toxicity involving fertility problems, malformation, and insufficient body growth (Chapin et al. 1999; Soares et al. 2008).

As regards environmental NP, the name indicates not any single molecule, but rather a technical mixture designated by no. CAS 84852-15-3 and involving more than 100 substitution isomers (Guenther et al. 2006; Wheeler et al. 1997). In order to render NP data more reliable and reproducible, it would be advisable that a clearly defined molecule of branched NP isomer be used as the reference standard in assessment of NP exposure.

Taking into account the fact that in most drinking water treatment plants, routine operations are concluded by a chlorination step, the formation of chlorinated derivatives of BPA or NP in drinking water is to be expected (Deborde et al. 2004; Deborde and von Gunten 2008; Gallard et al. 2004; Yamamoto and Yasuhara 2002). Furthermore, various forms of chlorinated BPA (mono-, di-, tri-, and tetra-chloro BPA) have been detected in wastewater from waste paper recycling plants (Fukazawa et al. 2002). On the other hand, only limited data are available concerning chlorinated NP derivatives and none of these compounds have been found in analyzed water. Moreover, chlorinated BPA has been detected in adipose tissue (Fernandez et al. 2007). Except for tetra-chloro-BPA, BPA and NP chlorinated derivatives are not used in industrial activity (Polo et al. 2006). Therefore, the only source of exposure to chlorinated derivatives is likely to be chlorine-treated water. Last but not least, estrogenic activity of chlorinated derivatives may be higher than in parent compounds (Fukazawa et al. 2002; Hu et al. 2002).

Different analytical methods have been developed so as to monitor and quantify endocrine-disrupting chemicals. Gas chromatography coupled to mass spectrometry (GC-MS) and liquid chromatography coupled to mass spectrometry (LC-MS) have recently been used. One advantage of LC-MS is that it does not require a derivatization step. Isotope dilution–MS/MS using a selected reaction monitoring acquisition mode has been found to maximally improve selectivity and sensitivity when measuring trace levels of environment chemicals (Vandenberg et al. 2007).

In the literature, different NP products have been used to prepare standard solutions: technical mixture (CAS 84852-15-3) (Loos et al. 2010; Petrovic et al. 2001, 2003), linear chain (4-n-NP; CAS 104-40-5) (Lagana et al. 2004; Li et al. 2010; Stavrakakis et al. 2008), or linear mixture (CAS 241-545-23) (Stackelberg et al. 2007). Some papers do not mention the exact NP product used (Li et al. 2010; Liu et al. 2004).

The NP technical mixture is designated by no. CAS 84852-15-3 and involves more than 100 substitution isomers (Guenther et al. 2006; Wheeler et al. 1997). In the literature, experimenters have used about ten single isomers of branched para-NP of which the relative contents vary in accordance with the manufacturers and the batches (Katase et al. 2008), thereby indicating that as concerns the reproducibility of the batches, industrial manufacturing methods have yet to be totally mastered. Use of the NP technical mixture as the standard compound may consequently lead to a discordance in isomer proportions between NP standard solution and NP present in environment (Kim et al. 2005). Moreover, since fragmentation of different isomers fails to yield the same fragments (Bhatt et al. 1992), use of an NP mixture will produce uncontrolled variable MS signal intensity between standards and unknowns, thereby leading to inexact results.

On the other hand, use of 4-n-NP (linear chain) as the standard compound may not be appropriate in environmental analyses because technical mixtures used in industrial
applications do not contain 4-n-NP (Katase et al. 2008). Therefore, 4-n-NP should not be the NP isomer present in the environment.

Taking all the above factors into account, a clearly defined molecule of branched NP isomer with a known degree of purity has got to be chosen from the mixture, so as to function as a standard. 353NP is the most abundant isomer (15–20 %) in three available commercial technical mixtures (TCI, Aldrich, Fluka) (Katase et al. 2008). Furthermore, 353NP is the compound exhibiting one of the highest levels of estrogenic activity (Preuss et al. 2006). Consequently, 353NP has been chosen as the NP standard.

The aim of this study was to develop an accurate and reproducible method to determine levels of BPA, 353-nonylphenol (353NP, used as a clearly defined standard) and chlorinated derivative concentration in order to investigate their occurrence in surface and treated water samples taken from all the drinking water treatment plants (DWTP) producing drinking water from surface water in the Poitou-Charentes area (France).

Materials and methods

Commercial chemicals and reagents

BPA (CAS 80-05-7) and internal standard bisphenol A-d16 (CAS 96210-87-6) were obtained from Sigma-Aldrich, Inc (St Louis, MO, USA). Methanol, hexane, acetone, ethyl acetate, and dichloromethane of high analytical grade (Pestipur®) quality were purchased from SDS (Peypin, France). Sodium thiosulfate was purchased from Sigma-Aldrich, Inc Water was pre-treated by a Purelab Prima® (Pestipur®) quality were purchased from SDS (Peypin, France). Nitrogen alphagaz-1 was purchased from Air Liquide (Paris, France).

Synthesis of 353-nonylphenol, chlorinated 353-nonylphenol and chlorinated bisphenol A

Chlorinated BPA, 353-nonylphenol: (a diastereomer mixture of 4-(3,5-dimethylheptan-3-yl)phenol named 353NP) and chlorinated 353-nonylphenol were custom synthesized by @rtMolecule (Poitiers, France). Briefly, chlorinated BPA (CBPA, 2,6-DCBPA, TCBPA, 353NP, C353NP, and DC353NP) was synthesized in the present study was 353NP-E/353NP-Z=45:55 (according to the nomenclature proposed by Katase et al. 2008). The purity and chemical structure of these compounds are shown in Table 1.

Water samples

Surface and treated water (SW and TW) samples were collected from the eight municipal drinking water treatment plants located in the French Poitou-Charentes area. One sample (250 ml) was performed at three different days and samples were pooled before analysis. SW samples were directly collected at the river surface above the DWTP. TW samples were collected at the outlet pipe of the treatment plant. TW samples were stored with the addition of a reducer (5 mg of sodium thiosulfate/250 mL) in order to stop chlorination of target compounds; all samples were kept frozen at −20°C until analysis.

Preparation of standard solutions

A 200-mg/L methanol stock solution of each compound (BPA, CBPA, 2,6-DCBPA, 2,2'-DCBPA, TCBPA, 353NP, C353NP, and DC353NP) was stored at +4°C. Extemporaneously, the initial stock solutions were diluted in methanol/water 50:50 (v/v) to obtain working standard solutions at 2, 4, 8, 20, and 40 μg/L (MeOH-standard). Internal standard solution (BPA-d16) was prepared in methanol/water 50:50 (v/v) at 20 μg/L from initial stock solution (200 mg/L).

Solid-phase extraction

Prior to the extraction, 1.25 mL of methanol and 100 μL of the internal standard solution (BPA-d16, 50 μg/L) were added to an aliquot of 250 mL of water sample. Water samples were extracted by solid-phase extraction (SPE). The SPE procedure for clean-up and concentration of water samples was performed using a glass C18 upti-clean® end-capped cartridge 200 mg (Interchim, Montluçon, France).

Cartridges were conditioned with 4 mL of dichloromethane/ethyl acetate (2:1; v/v) and then equilibrated with 5 mL of purified water. Water samples (250 mL) were passed through the wet cartridges, washed with 5 mL of purified water and dried for 15 min. For all these steps, flow rate was set at 10 mL/min. Elution were performed with a mixture of hexane/dichloromethane 50:50 (v/v) (2×2 mL) and a mixture of methanol/acetone/ethyl acetate 2:2:1 (v/v/v; 2×2 mL) at a flow rate of 2 mL/min. Extracts were evaporated at 40°C to dryness under a gentle nitrogen stream. Residues were dissolved in 250 μL of a purified water/methanol (50:50) solution. Finally, 25 μL of extract were injected onto LC-MS-MS apparatus.
Table 1 Purity and chemical structure of BPA, NP, and chlorinated derivatives

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Purity</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPA</td>
<td>HPLC &gt;99%&lt;sup&gt;a&lt;/sup&gt;</td>
<td><img src="image" alt="Structure of BPA" /></td>
</tr>
<tr>
<td>2-chloro-4-[1-(4-hydroxy-phenyl)-1-methyl-ethyl]-phenol</td>
<td>CBPA</td>
<td>HPLC &gt;98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2,6-Dichloro-4-[1-(4-hydroxy-phenyl)-1-methyl-ethyl]-phenol</td>
<td>2,6-DCBPA</td>
<td>HPLC 98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2-chloro-4-[1-(3-chloro-4-hydroxy-phenyl)-1-methyl-ethyl]-phenol</td>
<td>2,2'-DCBPA</td>
<td>HPLC &gt;99%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2,6-Dichloro-4-[1-(3-chloro-4-hydroxy-phenyl)-1-methyl-ethyl]-phenol</td>
<td>TCBPA</td>
<td>HPLC &gt;98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>4-(1-ethyl,1,3-dimethyl-pentyl)-phenol</td>
<td>353NP</td>
<td>GC &gt;98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2-chloro-4-(1-ethyl,1,3-dimethyl-pentyl)-phenol</td>
<td>C353NP</td>
<td>GC &gt;98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2,6-Dichloro-4-(1-ethyl,1,3-dimethyl-pentyl)-phenol</td>
<td>DC353NP</td>
<td>GC &gt;98%&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Sigma Aldrich  
<sup>b</sup> @rt molecule

LC-MS-MS analysis

Concentration of BPA, 353NP, and chlorinated derivatives were determined using a LC/MS/MS system consisting of an HPLC ultimate 3000 (Dionex, Sunnyvale, USA), coupled to an API 4000 triple quadrupole mass spectrometer (Applied Biosystems, Forster City, CA, USA).

HPLC column was a supercosil ABZ<sup>®</sup> (3 μm particle size, 150×4.6 mm; Supelco, St Louis, USA). BPA and chlorinated BPA analysis was carried out using a solvent gradient program at a flow rate of 1 mL/min. Initial condition of the mobile phase was methanol/water 50:50 (v/v) for 5 min. The gradient was programmed to linearly increase the amount of methanol up to 99% for 10 min. To clean up the column, methanol was kept constant at 99% during 5 min. 353NP and chlorinated 353NP were analyzed using a solvent isocratic program; mobile phase composition was methanol/water 85/15 (v/v).

The MS-MS was equipped with an atmospheric pressure chemical ionization (APCI) interface, operating in negative ionization mode. Quantitative analysis was carried out in the multiple reaction monitoring mode (MRM), using two specific combinations of a precursor–product ion transition for each compound. Precursor–product transitions as well as their...
corresponding collision energies are shown in Table 2. MS/MS
detector conditions were set as follows: ion source gas 150 psig;
probe temperature 550°C; curtain gas 20 psig; collision gas
9 psig, entrance potential −5.0 V, and nebulizer current −1.

Blank, linearity, and recovery

NP (including 353NP) and BPA contaminations could arise
from laboratory accessories, reagent, SPE procedure, and
apparatus. In order to avoid any contamination, only pre-
treated glassware (500°C, 5 h), teflon seals, and high-quality
solvent were used throughout the study. Two kinds of blanks
were performed: the first blank was purified water with addi-
tion of sodium thiosulfate as a sample loading step, on which
SPE procedure was carried out, and the second was obtained
by SPE procedure without any sample loading step.

Linearity of the chromatographic response was assessed
on three different days using standard curves including five
calibration points ranging from 2 to 40 ng/L.

Recovery was determined by analysis of ten natural water
samples (exempt of target compounds) spiked at two differ-
cent concentrations (20 and 40 ng/L). The recovery value
includes matrix effect and losses during SPE.

Limit of detection and limit of quantification

The limit of detection (LOD) and the limit of quantification
(LOQ) were calculated as three and ten times the signal-to-
oise (S/N) ratio, respectively, using blanks and MeOH-
standard. BPA-d16 was added before sample treatment and
used as an internal standard for all target compounds since
corresponding labeled standards were not readily available.
To estimate the method limit of detection (mLOD) and the
method limit of quantification (mLOQ), the LOD and LOQ
values were corrected by the recovery of each compound.

Intra-day and inter-day coefficients of variation

Sample concentrations were determined for each compound
using the corresponding MeOH standard curve calibration
and corrected by the recoveries. BPA-d16 recovery was
checked in order to confirm that the extraction step had
been correctly performed. Intra-day coefficient of variation
was obtained with five replicates of quality control sample
at 20 ng/L. Inter-day coefficient of variation was obtained
from experiments performed on three separate days with
two replicates of quality control sample at the same concen-
tration. Accuracy was determined during inter-day and intra-
day assessments.

Results

Analytical performance

BPA and 353NP were detected in blank extracts but at a
lower level than limit of quantification (Figs. 1a and 2a). On
the other hand, no chlorinated derivatives were detected.

Table 2  MS/MS parameters of BPA, NP, and chlorinated derivatives

<table>
<thead>
<tr>
<th>Compound</th>
<th>Retention time (min)</th>
<th>MRM (m/z)</th>
<th>Declustering potential (V)</th>
<th>Collision energy (V)</th>
<th>Collision cell exit potential (V)</th>
<th>Dwell time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPA</td>
<td>12.18</td>
<td>227–212</td>
<td>−90</td>
<td>−40</td>
<td>−20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>227–133</td>
<td>−90</td>
<td>−40</td>
<td>−20</td>
<td>40</td>
</tr>
<tr>
<td>CBPA</td>
<td>13.72</td>
<td>261–182</td>
<td>−80</td>
<td>−30</td>
<td>−29</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>261–133</td>
<td>−80</td>
<td>−30</td>
<td>−29</td>
<td>40</td>
</tr>
<tr>
<td>2,6-DCBPA</td>
<td>14.59</td>
<td>295–280</td>
<td>−80</td>
<td>−40</td>
<td>−30</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>297–282</td>
<td>−80</td>
<td>−40</td>
<td>−30</td>
<td>40</td>
</tr>
<tr>
<td>2,2′-DCBPA</td>
<td>14.84</td>
<td>295–201</td>
<td>−100</td>
<td>−52</td>
<td>−6</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>297–203</td>
<td>−100</td>
<td>−52</td>
<td>−6</td>
<td>40</td>
</tr>
<tr>
<td>TCBPA</td>
<td>15.51</td>
<td>329–253</td>
<td>−100</td>
<td>−52</td>
<td>−6</td>
<td>40</td>
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<tr>
<td></td>
<td></td>
<td>331–255</td>
<td>−100</td>
<td>−52</td>
<td>−6</td>
<td>40</td>
</tr>
<tr>
<td>353NP</td>
<td>4.45</td>
<td>219–133</td>
<td>−70</td>
<td>−35</td>
<td>−20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>219–147</td>
<td>−70</td>
<td>−26</td>
<td>−11</td>
<td>40</td>
</tr>
<tr>
<td>C353NP</td>
<td>4.69</td>
<td>253–167</td>
<td>−80</td>
<td>−5</td>
<td>−3</td>
<td>40</td>
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<tr>
<td></td>
<td></td>
<td>253–282</td>
<td>−80</td>
<td>−40</td>
<td>−13</td>
<td>40</td>
</tr>
<tr>
<td>DC353NP</td>
<td>4.89</td>
<td>287–201</td>
<td>−90</td>
<td>−5</td>
<td>−3</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>287–216</td>
<td>−80</td>
<td>−40</td>
<td>−13</td>
<td>40</td>
</tr>
<tr>
<td>BPA-d16</td>
<td>12.02</td>
<td>241–221</td>
<td>−90</td>
<td>−30</td>
<td>−20</td>
<td>40</td>
</tr>
</tbody>
</table>
Fig. 1 LC-MS-MS chromatogram at quantification transition of BPA, CBPA, 2,6-DCBPA, 2,2'-DCBPA, and TCBPA of a blank, b standard solution corresponding at 20 ng/L, and c surface water sample.
Loading or not loading purified water before SPE procedure as a sample produced similar results. Moreover, no trace of BPA, either 353NP or chlorinated derivatives was detected from direct injection of the solvents used. Altogether, BPA and 353NP contaminations seem to arise from the extraction procedure and have been taken into account in the calculation method.

Calibration curves of BPA, 353NP, chlorinated BPA, and chlorinated 353NP provided adequate linearity as shown by the correlation coefficients, which are greater than 0.99. Chromatograms of a standard corresponding at 20 ng/L are presented in Figs. 1b and 2b. BPA and chlorinated BPA extractions yielded high levels of recovery. However, due to poor extraction recovery of C353NP, a high degree of variability was observed. Therefore, C353NP quantification could not be performed. Results are presented in Table 3.

The developed method showed similar low values of mLOD and mLOQ for BPA, CBPA, 2,6-DCBPA, 2,2′-DCBPA TCBPA, and 353NP. In contrast, C353NP and DC353NP showed higher limits (Table 3).

Intra-day and inter-day variation obtained from quality controls of the target compounds are shown in Table 3. The intra-day relative standard deviation (RSD) was ≤19 %, while accuracy was determined between 82.7 and 113.6 % at 20 ng/L. The inter-day relative standard deviation was ≤21 % and accuracy ranged from 85.0 to 112.0 %.

Water sample analysis

Appropriate internal quality controls were applied so as to assess the validity of the optimized analytical procedure and to verify that no outliers occurred during routine analysis sequences. Signal specificity was systematically checked by comparison of each retention time and fragmentation ratio with the corresponding standard. Calibration curves were regularly checked for linearity ($r^2$ ≥0.99). Moreover, quantification of quality control (20 ng/L) was regularly performed during DWTP water sample analysis (bias ≤11 %, RSD ≤17 %).

BPA was detected in concentrations ranging from 6.7 to 29.7 ng/L in SW with a median of 17.7 ng/L and from 2.0 to 16.9 ng/L in TW with a median of 7.2 ng/L (Table 4). 353NP was detected in concentrations ranging from 13.5 to 124.9 ng/L in SW with a median of 32.5 ng/L and from <mLOD to 59.4 ng/L in TW with a median of 8.0 ng/L (Table 4). BPA and 353NP chlorinated derivatives were lower than the mLOD. Chromatograms of a sample are presented in Figs. 1a and 2c.
Fig. 2  LC-MS-MS chromatogram at quantification transition of 353NP, C353NP, and DC353NP of a blank, b standard solution corresponding at 20 ng/L, and c surface water sample.
Discussion

Method optimization

Chlorinated BPA and chlorinated NP are produced during potabilization processes. Monochloro-, dichloro-, trichloro-, and tetrachloro-BPA are the main by-products formed during chlorination (Gallard et al. 2004; Yamamoto and Yasuhara 2002). Tetrachloro-BPA, which is commonly used as a flame retardant in polymers, is not of hydro origin alone (Polo et al. 2006). Consequently, in this study we did not search for tetrachloro-BPA.

While high-purity solvents were used, as was glass instead of plastics, and even though specific purification procedures were carried out, BPA and 353NP contamination could not be avoided, and were probably due to leaching effects during solid-phase extraction. Other studies have likewise reported BPA contamination from reagents or solvents or leaching from the materials during sampling, storage, processing, and analysis (Dekant and Volkel 2008; Gallart-Ayala et al. 2010). Similarly, NP contamination in blank has been described elsewhere (Loos et al. 2010). In the present study, BPA and 353NP contaminations did not exceed the limit of quantification, but special attention when proceeding remains advisable.

During MS parameter optimization, negative ionization mode produced higher signal intensity than positive ionization mode and a much better S/N for BPA and 353NP. APCI and ESI (electrospray) interfaces have been compared using both a methanol solution of compounds and spiked river water. ESI interface produced higher sensibility with a methanol solution but significant matrix effect was observed in spiked water extracts. The most satisfactory results, providing negligible matrix effect, were achieved using APCI interface, which was consequently chosen for the purposes of this study.

Water sample analysis

The main objective of this study was to inventory the French Poitou-Charentes area, with regards to the surface and treated water of DWTPs producing drinking water from surface water. So as to render unimportant the concentration variability according to time of sampling, extraction was carried out on three different days, and analysis was performed at each location from a « pool » of the three samplings. It should nonetheless be noted that initial variability was at its lowest for surface waters 3, 7, and 8, which came from water retention installations. It should also be mentioned that the figures recorded in this study were obtained at
treatment plant entrance and exit, and thereby provide a snapshot image of real-time situations in each plant and can be meaningfully compared on initial examination (no mass balance calculations for the branch).

BPA was found in all the surface water samples analyzed. Our results are in agreement with those reported in the literature on DWTP water samples (Gallart-Ayala et al. 2010; Lagana et al. 2004; Loose et al. 2010; Rodriguez-Mozaz et al. 2004; Stackelberg et al. 2007; Stavrakakis et al. 2008).

In most DWTPs a decrease between SW and TW was observed (1-2-3-4-6-7), ranging from 36.6 to 78.9 % with a median of 75.2 %. Authors from different countries have reported similar results with overall elimination ranging from 70.0 to 100.0 % (Gallart-Ayala et al. 2010; Rodriguez-Mozaz et al. 2004; Stackelberg et al. 2007; Stavrakakis et al. 2008). The processes performed in water treatment plants are known to decrease BPA. First of all, most BPA is eliminated during the chlorination step of DWTP due to its high reactivity with chlorine (Deborde et al. 2004; Gallard et al. 2004; Gallart-Ayala et al. 2010; Stackelberg et al. 2007). All the DWTPs mentioned in this study include a chlorination step. A sand filtration step has likewise been shown to remove BPA in DWTP (Gallart-Ayala et al. 2010; Rodriguez-Mozaz et al. 2004). Moreover, ozonation has been suggested as an effective means of eliminating BPA (Deborde et al. 2008; Nakada et al. 2007). Finally, activated carbon is known to adsorb hydrophobic compounds, including BPA (Rodriguez-Mozaz et al. 2004; Stackelberg et al. 2007). Different operatory combinations of these water treatment processes are applied in the different Poitou-Charentes area DWTPs (Table 5).

Table 3: Linearity, recovery data, limits of detection, and limits of quantification (nanograms per liter) for determination of BPA, 353NP, and their chlorinated derivatives

<table>
<thead>
<tr>
<th>Compound</th>
<th>Linearity (n=3) r²&gt;</th>
<th>Recoverya % (RSDb, n=10)</th>
<th>mLODc (ng/L)</th>
<th>mLOQd (ng/L)</th>
<th>Intra-day mean (n=5)</th>
<th>Inter-day mean (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracye (%)</td>
<td>RSDb (%)</td>
</tr>
<tr>
<td>BPA</td>
<td>0.999</td>
<td>108 (17)</td>
<td>0.5</td>
<td>1.5</td>
<td>107.6</td>
<td>7</td>
</tr>
<tr>
<td>CBPA</td>
<td>0.992</td>
<td>99 (18)</td>
<td>0.7</td>
<td>2.0</td>
<td>113.6</td>
<td>8</td>
</tr>
<tr>
<td>2,6-DCBPA</td>
<td>0.998</td>
<td>101 (19)</td>
<td>0.4</td>
<td>1.0</td>
<td>94.8</td>
<td>8</td>
</tr>
<tr>
<td>2,2'-DCBPA</td>
<td>0.998</td>
<td>100 (21)</td>
<td>0.3</td>
<td>1.0</td>
<td>104.6</td>
<td>14</td>
</tr>
<tr>
<td>TCBPA</td>
<td>0.998</td>
<td>88 (17)</td>
<td>2.3</td>
<td>6.8</td>
<td>102.0</td>
<td>19</td>
</tr>
<tr>
<td>353NP</td>
<td>0.997</td>
<td>49 (19)</td>
<td>1.4</td>
<td>4.1</td>
<td>98.3</td>
<td>6</td>
</tr>
<tr>
<td>C353NP</td>
<td>0.998</td>
<td>7 (68)</td>
<td>63.0</td>
<td>NDf</td>
<td>NDf</td>
<td>NDf</td>
</tr>
<tr>
<td>DC353NP</td>
<td>0.998</td>
<td>38 (15)</td>
<td>4.7</td>
<td>15.5</td>
<td>96.0</td>
<td>7</td>
</tr>
<tr>
<td>BPA-d16</td>
<td>NDf</td>
<td>99 (19)</td>
<td>NDf</td>
<td>NDf</td>
<td>NDf</td>
<td>NDf</td>
</tr>
</tbody>
</table>

Intra-day and inter-day variation obtained from quality control samples at 20 ng/L

a Expressed as [(mean observed concentration)/(nominal concentration)]×100

b Relative standard deviation
c Method limit of detection
d Method limit of quantification
e Expressed as [(mean observed concentration)/(nominal concentration)]×100
f Not determined

BPA was found in all the treated water samples analyzed. In most DWTPs a decrease between SW and TW was observed (1-2-3-4-6-7), ranging from 36.6 to 78.9 % with a median of 75.2 %. Authors from different countries have reported similar results with overall elimination ranging from 70.0 to 100.0 % (Gallart-Ayala et al. 2010; Rodriguez-Mozaz et al. 2004; Stackelberg et al. 2007; Stavrakakis et al. 2008). The processes performed in water treatment plants are known to decrease BPA. First of all, most BPA is eliminated during the chlorination step of DWTP due to its high reactivity with chlorine (Deborde et al. 2004; Gallard et al. 2004; Gallart-Ayala et al. 2010; Stackelberg et al. 2007). All the DWTPs mentioned in this study include a chlorination step. A sand filtration step has likewise been shown to remove BPA in DWTP (Gallart-Ayala et al. 2010; Rodriguez-Mozaz et al. 2004). Moreover, ozonation has been suggested as an effective means of eliminating BPA (Deborde et al. 2008; Nakada et al. 2007). Finally, activated carbon is known to adsorb hydrophobic compounds, including BPA (Rodriguez-Mozaz et al. 2004; Stackelberg et al. 2007). Different operatory combinations of these water treatment processes are applied in the different Poitou-Charentes area DWTPs (Table 5).

Table 4: BPA and 353NP concentrations (nanograms per liter) in untreated and treated water from Poitou-Charentes drinking water treatment plants (DWTP)

<table>
<thead>
<tr>
<th>DWTP</th>
<th>BPA value (method SDa)</th>
<th>353NP value (method SDa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface water</td>
<td>Treated water</td>
</tr>
<tr>
<td>1</td>
<td>21.2 (1.6)</td>
<td>5.2 (0.4)</td>
</tr>
<tr>
<td>2</td>
<td>25.1 (1.9)</td>
<td>5.3 (0.4)</td>
</tr>
<tr>
<td>3</td>
<td>29.7 (2.3)</td>
<td>10.8 (0.8)</td>
</tr>
<tr>
<td>4</td>
<td>22.3 (1.7)</td>
<td>4.7 (0.4)</td>
</tr>
<tr>
<td>5</td>
<td>6.7 (0.5)</td>
<td>13.7 (1.1)</td>
</tr>
<tr>
<td>6</td>
<td>8.0 (0.6)</td>
<td>2.0 (0.2)</td>
</tr>
<tr>
<td>7</td>
<td>14.2 (1.0)</td>
<td>9.0 (0.7)</td>
</tr>
<tr>
<td>8</td>
<td>8.0 (0.6)</td>
<td>16.9 (1.3)</td>
</tr>
</tbody>
</table>

a Standard deviation

b Limit of quantification
Table 5  Description of the treatment process of the eight drinking water treatment plants

<table>
<thead>
<tr>
<th>DWTP</th>
<th>Water origin</th>
<th>Preoxidation</th>
<th>Clarification</th>
<th>Interoxidation</th>
<th>Filtration</th>
<th>Postoxidation</th>
<th>Disinfection</th>
<th>Outlet residual chlorine (mg Cl₂/L)</th>
<th>Outlet pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>River (43 m³/s)</td>
<td>Coagulation/flocculation–sedimentation</td>
<td></td>
<td>Sand filtration–ozonation–GAC filtration</td>
<td>Sodium hypochlorite</td>
<td>0.6</td>
<td></td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>River (used only as water of supplement) (1 m³/s)</td>
<td>Coagulation/flocculation–sedimentation</td>
<td></td>
<td>Sand filtration</td>
<td>Gaseous chlorine</td>
<td>0.3</td>
<td></td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Dam water</td>
<td>Potassium permanganate</td>
<td>Coagulation/flocculation–flotation</td>
<td>Potassium permanganate</td>
<td>PAC–flocculation–sedimentation–ultrafiltration</td>
<td>Sodium hypochlorite</td>
<td>0.6</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>River (28 m³/s)</td>
<td>Ozonation</td>
<td>Coagulation/flocculation–PAC–sedimentation</td>
<td></td>
<td>Sand filtration</td>
<td>Ozonation</td>
<td>Gaseous chlorine</td>
<td>0.5</td>
<td>7.7</td>
</tr>
<tr>
<td>5</td>
<td>River with reservoir</td>
<td>Chlorine dioxide</td>
<td>Coagulation/flocculation–PAC–sedimentation</td>
<td></td>
<td>Sand filtration</td>
<td>Ozonation</td>
<td>Chlorine dioxide</td>
<td>0.6</td>
<td>7.9</td>
</tr>
<tr>
<td>6</td>
<td>River (1 m³/s)</td>
<td>Ozonation</td>
<td>Coagulation/flocculation–sedimentation</td>
<td>Potassium permanganate</td>
<td>Sand filtration–ozonation–GAC filtration</td>
<td>Sodium hypochlorite</td>
<td>0.7</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Dam water</td>
<td>Ozonation</td>
<td>Coagulation/flocculation–flotation</td>
<td>Potassium permanganate</td>
<td>Sand filtration–postozonation–GAC filtration</td>
<td>Sodium hypochlorite</td>
<td>0.7</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Dam water</td>
<td>Ozonation</td>
<td>Coagulation/flocculation–PAC–flotation</td>
<td>Ozonation</td>
<td>Sand filtration</td>
<td>Ozonation</td>
<td>Sodium hypochlorite</td>
<td>0.7</td>
<td>7.9</td>
</tr>
</tbody>
</table>

*GAC* granulated activation carbon, *PAC* powder activation carbon
Stackelberg et al. 2007). Stavrakakis et al. (2008) did not find any NP in DWTP water samples, maybe due to use of 4-n-NP as standard solution. 353NP was found in most of the treated water analyzed (3-4-5-8). 353NP concentration decreased in most of the DWTP TW samples (1-2-4-6-7) from 2.2 to 100.0 %, with a median of 100.0 %. Authors from different countries have reported similar results with overall elimination ranging from 73.0 to 100.0 % (Petrovic et al. 2001). Unlike BPA, only the chlorination step allows for effective removal of NP during water treatment process (Petrovic et al. 2001, 2003; Stackelberg et al. 2007).

Contradictorily to some of the other results, we found BPA and 353NP in TW samples, probably because they were not totally eliminated during the different steps of the DWTP process (Gallart-Ayala et al. 2010; Petrovic et al. 2001). Another hypothesis is that BPA and NP are formed during drinking water production and transport (Yamamoto and Yasuhara 2002).

On the other hand, we found more BPA and 353NP in some TW samples than in corresponding SW, probably because some BPA or 353NP were released during drinking water production and transport (Loyo-Rosales et al. 2004).

Chlorinated derivatives were not detected in samples collected in either DWTP in surface or in treated water. This is probably due to the mLOD obtained in our conditions. Gallart-Ayala et al. (2010) reported similar results for chlorinated BPA derivatives and Petrovic et al. (2003) for chlorinated NP derivatives. Up until now, BPA chlorinated derivatives have been detected in environment only in effluent from wastepaper recycling plants, where BPA concentrations are much higher than in DWTP (Fukazawa et al. 2002).

This study took place in Poitou-Charentes, a semirural French area with 1.7 million inhabitants. Seventeen percent of the Poitou-Charentes population is supplied with drinking water produced from surface water, 19 % from a mixture of surface water and groundwater and 64 % from groundwater. The Poitou-Charentes area contains eight DWTPs, and the drinking water produced from surface water is meant to supply approximately 0.6 million inhabitants. All of the water intakes from the treatment plants were subjected to environmental study prior to operation in order to determine, at each site, the proximate, nearby, and eventually distant protection perimeters or buffer zones as defined in article L1321-2 of the French public health code. Since BPA and 353NP were present in all the surface water samples, the results clearly show that Poitou-Charentes, 25,810 km², a mainly rural (agriculture, livestock, and forests) and slightly urbanized French region (ten towns with more than 15,000 inhabitants, including three cities with population ranging from 60,000 to 90,000), is particularly affected by endocrine disruptor compounds, which characterize chronic surface water pollution. Indeed, several plastic and composite factories liable to use BPA and NP are present in Poitou-Charentes, albeit not close to the DWTPs studied. In addition, the manufacturing of agricultural products containing NPEOs as surfactants may constitute another source of NP.

Conclusion

The analytical method developed in this work confirms that BPA and NP analysis require specific procedures in order to avoid contamination by ubiquitous endocrine disruptor compounds (EDC). If 353NP has already been used in some studies assessing the toxicity potency of nonylphenols, to our knowledge, no study has aimed at quantifying 353NP in environment. In this study, for the first time, 353NP has been characterized in environmental water, and the results on nonylphenol achieved with this substance of reference (353NP) may allow for comparison with future results obtained under the same conditions.

This paper puts forward the first simultaneous assessment of BPA, 353NP, and their chlorinated derivatives in DWTP surface and treated water samples. Whole surface water used for drinking water in Poitou-Charentes area contains BPA and 353NP. Operations in DWTPs have yielded efficient removal of these EDCs but have not eliminated them completely. Moreover, our results suggest possible BPA and NP formation during water treatment. The occurrence of these EDCs in finished water may indicate that drinking water could be a source of human exposure. In order to evaluate this risk and contribute to epidemiological studies, the monitoring of EDCs in both tap water and human tissue is to be recommended. Chlorinated derivatives of BPA and 353NP were not detected in the surface and treated water of the Poitou-Charentes DWTPs. Nevertheless, chlorinated BPA has been detected in biologic tissue (Fernandez et al. (2007)) likely coming from treated water. It may be added that the treated water analyzed at the exit of DWTP is not the tap water finally consumed. That much said, BPA and NP leaching from plastic pipes of distribution systems may react with the chlorine present in treated water, thereby producing chlorinated derivatives, which could potentially be present in consumer tap water. Further investigations involving consumer tap water consequently need to be performed.

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