Food Additives and Contaminants
Vol. 26, No. 6, June 2009, 928–937

Migration of bisphenol A from plastic baby bottles, baby bottle liners and reusable polycarbonate drinking bottles

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(*Received 18 November 2008; final version received 21 December 2008*)

Human exposure to bisphenol A (BPA) has recently received special attention. It has been shown that exposure to BPA may occur through the consumption of beverages or foods that have been in contact with polycarbonate (PC) plastic containers or epoxy resins in food packaging. A BPA migration study was conducted using a variety of plastic containers, including polycarbonate baby bottles, non-PC baby bottles, baby bottle liners, and reusable PC drinking bottles. Water was used to simulate migration into aqueous and acidic foods; 10% ethanol solution to simulate migration to low- and high-alcoholic foods; and 50% ethanol solution to simulate migration to fatty foods. By combining solid-phase extraction, BPA derivatization and analysis by GC-EI/MS/MS, a very low detection limit at the $ng\,l^{-1}$ level was obtained. Migration of BPA at 40°C ranged from $0.11\,\mu g\,l^{-1}$ in water incubated for 8 h to $2.39\,\mu g\,l^{-1}$ in 50% ethanol incubated for 240 h. Residual BPA leaching from PC bottles increased with temperature and incubation time. In comparison with the migration observed from PC bottles, non-PC baby bottles and baby bottle liners showed only trace levels of BPA. Tests for leachable lead and cadmium were also conducted on glass baby bottles since these represent a potential alternative to plastic bottles. No detectable lead or cadmium was found to leach from the glass. This study indicated that non-PC plastic baby bottles, baby bottle liners and glass baby bottles might be good alternatives for polycarbonate bottles.

Keywords: bisphenol A (BPA); migration; polycarbonate; baby bottles; GC/EI-MS/MS

Introduction

In recent years, new concerns regarding the health impacts of emerging endocrine-disrupting chemicals on newborns have arisen. One of these chemicals, bisphenol A (BPA), has recently received particular attention from the public and the scientific community. BPA is an industrial monomer used to make polycarbonate (PC) plastic and epoxy resins. PC is used in a number of consumer products, including baby bottles and reusable water bottles. Epoxy resins are mainly used as a protective lining on the inside of metal-based food and beverage cans. Several studies have shown that BPA may be associated with a number of health problems and diseases. Although BPA is quickly metabolized to BPA monoglucuronide and rapidly excreted in urine in adults (Volkel 2002; Tominaga et al. 2006), some residual free BPA is still available for receptor binding (European Food Safety Authority (EFSA) 2006). Studies on BPA low-dose effects have been summarized elsewhere (Vom Saal and Hughes 2005). Potential adverse human health effects observed in experimental animals exposed to low doses of BPA include an increase in prostate and breast cancer, urogenital abnormalities in male babies, a decline in semen quality in men, early onset of puberty in girls, metabolic disorders including insulin-resistant (type 2) diabetes and obesity, and neurobehavioral problems such as attention deficit hyperactivity disorder (Vom Saal et al. 2007). Recently, an Expert Panel composed of a group of twelve independent scientists was convened by the US National Toxicology Program (NTP) Center for the Evaluation of Risks to Human Reproduction (CERHR) to evaluate BPA. The panel concluded that, based on approximately 500 studies reviewed, the likelihood of human reproductive problems is 'minimal' or 'negligible'. However, the panel expressed 'some concern' that exposure to BPA could have neurological or behavioural effects in foetuses, infants, and children. It also expressed 'minimal concern' that *in utero* exposure to BPA has a negative effect on the prostate, produces birth defects and malformations, and potentially causes accelerations in puberty. For adults, the panel expressed 'negligible concern' for adverse reproductive effects following exposures to BPA in the general population (NTP 2008). A recent epidemiological study

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ISSN 0265–203X print/ISSN 1464–5122 online

DOI: 10.1080/02652030802706725
http://www.informaworld.com

investigated the association of urinary concentrations of BPA and health effects in the US population. Data from that study revealed that higher concentrations of urinary BPA were associated with an increased prevalence of cardiovascular diseases, diabetes, and liver enzyme abnormalities. However, the authors of the study recognized that independent replication and follow-up studies were still needed in order to confirm their observations, and to provide further evidence on whether the associations are causal (Lang et al. 2008).

The most likely major sources of dietary exposure are believed to be migration of BPA into food and beverages from BPA-containing packaging materials that are in direct contact with food, and migration from PC containers such as baby bottles and reusable drinking bottles. Recently, the Government of Canada conducted a screening assessment of BPA that focused primarily on the risk of BPA to newborns and infants up to 18 months of age. A precautionary approach was applied in characterizing BPA risk for two reasons: toxicokinetics and metabolism data indicate a potential sensitivity of the pregnant woman, foetus and infant; and animal studies suggest a trend towards heightened susceptibility during developmental stages in rodents. The risk assessment concluded that the neurodevelopmental and behavioural data set in rodents, though highly uncertain, is suggestive of potential effects at doses at the same order of magnitude to one to two orders of magnitude higher than exposures of infants and newborns. Following that screening assessment, the Government of Canada announced a series of measures to reduce BPA exposure to infants and newborns by proposing a number of actions, including a ban on the import, sale, and advertising of PC baby bottles and listing BPA as a toxic substance under Schedule 1 of the Canadian Environmental Protection Act, 1999 (Department of the Environment and Department of Health, Canada 2008). Potential health effects that might be caused by the leaching of BPA from PC containers are leading the industry to develop market alternatives.

Although several studies have been conducted on the migration of BPA from PC bottles into food simulants under a variety of conditions (Biles et al. 1997; Mountfort et al. 1997; Kawamura et al. 1998; Sun et al. 2000; D'Antuono et al. 2001; Brede et al. 2003; Wong et al. 2005; Miyamoto and Kotake 2006; Maragou et al. 2008; Biedermann-Brem et al. 2008; Cao and Corriveau 2008; Ehlert et al. 2008; Le et al. 2008), to the best of our knowledge, there are no data on the migration of BPA from PC baby bottle substitutes, including bottles commonly labelled 'non-BPA' or 'BPA-free', or the leaching of toxic metals from glass baby bottles. To contribute to an understanding of the conditions of oral intake of BPA, its migration was studied in different brands of PC and non-PC baby bottles, baby bottle liners, and new and used PC drinking bottles sold by Canadian supply retailers. Different experimental conditions were adopted from the US Food and Drug Administration's (USFDA) *Guidance for Industry: Preparation of Pre-market Submissions for Food Contact Substances: Chemistry Recommendations* (2007) to cover repeated normal use and worst case scenarios. All samples were analysed using a method combining solid-phase extraction and GC/EI-MS/MS. Polymeric materials used in non-PC baby bottles were characterized by Fourier transform infrared spectrometer (FTIR), and the glass baby bottles were tested for leachable lead and cadmium.

Materials and methods

Standards and reagents

BPA standard (99%) was purchased from AccuStandard (New Haven, CT, USA). ^{13}C-BPA standard was obtained from Cambridge Isotope Laboratories (Andover, MA, USA). Reagent-grade ethanol was obtained from Caledon Laboratories Ltd (Georgetown, ON, Canada). Methanol and acetone, GC grade, and high-performance liquid chromatography (HPLC)-grade water were purchased from EMD Chemicals, Inc. (Gibbstown, NJ, USA). Trifluoroacetic acid (TFA, 98%) was obtained from Sigma Chemical Co. (St Louis, MO, USA). *N*-methyl-*N*-(trimethylsilyl)trifluoroacetamide (MSTFA, 98.1%) was purchased from Regis Technologies, Inc. (Morton Grove, IL, USA).

Food simulant

Food simulants used in this study are those outlined in USFDA (2007). HPLC-grade water (HPLC-grade BPA-low water, also called 'water' here) was used to simulate migration to aqueous and acidic foods, 10% ethanol/HPLC water solution to simulate migration to low- and high-alcoholic foods, and 50% ethanol/HPLC water solution to simulate migration to fatty foods (e.g. infant formula).

Baby bottle samples, temperature and time of testing

Repeated normal use

As baby bottles are typically used with their contents kept near body temperature, the migration testing using new baby bottles was carried out at 40°C according to USFDA (2007) for three time periods: 8, 24 and 240 h. The 10-day (240-h) testing period was included in order to mimic repetitive use of baby bottles.

Dishwashing

The impact of dishwashing was investigated on selected baby bottles. Nine different brands of baby bottles were cleaned before first-time use according to the manufacturer's instructions. The bottles were then filled with water and, after being heated to 40°C in a hot water bath, were left at room temperature for 2 h before sample clean-up and pre-concentration using solid-phase extraction (SPE). The experiment was repeated daily with the same bottles over a six-day period; the bottles were washed in a domestic dishwasher (55°C) between tests. For each dishwashing procedure, water was collected at the beginning of the initial cycle and at the first and final detergent washes; the respective pH values were 8.85, 10.28 and 9.66.

PC baby bottles, non-PC baby bottles, and baby bottle liners

PC baby bottles, non-PC baby bottles, and baby bottle liners were used for high-temperature testing. A new baby bottle or liner was used for each test. Baby bottles and baby bottle liners representing brands sold in Canada were purchased across the country and supplied by the Consumer Product Safety Bureau, Health Canada. After filling the bottles or liners with boiling water or 10% ethanol at 85°C, the samples were held at 60°C for 2, 22, 94 and 238 h. The bottles were left at room temperature for 2 h before sample preconcentration using SPE. Table 1 lists the baby bottles and liners used in the study and the description of the test applied.

Table 1. Bisphenol A (BPA) migration testing procedures applied to baby bottles and liners.

			Migration testing method		
Container brand	Volume (ml)	Recycling symbol	Water	10% EtOH	50% EtOH
Baby bottles					
BB-01	260	PES	Repeated use; dishwashing; high temperature	High temperature	Repeated use
BB-02	150	PP '5'	Repeated use; high temperature	High temperature	Repeated use
BB-03	250	PC '7'	Repeated use; high temperature	–	Repeated use
BB-04	270	PC '7'	Repeated use; dishwashing; high temperature	–	Repeated use
BB-05	260	PC '7'	Repeated use; high temperature	–	Repeated use
BB-06	240	PC '7'	Repeated use; dishwashing; high temperature	–	Repeated use
BB-07	250	PC '7'	Repeated use; high temperature	–	Repeated use
BB-08	240	PC '7'	Repeated use; dishwashing; high temperature	–	Repeated use
BB-09	250	PC '7'	Repeated use; dishwashing; high temperature	–	Repeated use
BB-10	260	PC '7'	Repeated use; dishwashing, high temperature	–	Repeated use
BB-11	250	PC '7'	Repeated use; high temperature	–	Repeated use
BB-12	250	PC '7'	Repeated use; dishwashing; high temperature	–	Repeated use
BB-13	240	PC '7'	Repeated use; high temperature	–	Repeated use
BB-14	240	PC '7'	Repeated use; high temperature	–	Repeated use
BB-15	180	PC '7'	Dishwashing; high temperature	High temperature	–
BB-16	240	PC '7'	High temperature	High temperature	–
BB-17	270	PP '5'	High temperature; dishwashing	High temperature	–
BB-18	180	PES	High temperature	High temperature	–
BB-19	300	PES	High temperature	High temperature	–
BB-20	220	n.a.	High temperature	High temperature	–
BB-21	240	PP '5'	High temperature	High temperature	–
BB-22	120	PP '5'	High temperature	High temperature	–
BB-23	240	PP '5'	High temperature	High temperature	–
BB-24	240	n.a.	High temperature	High temperature	–
Bottle liners					
Liner-01	236	LDPE '4'	High temperature	High temperature	–
Liner-02	118	LDPE '4'	High temperature	High temperature	–
Liner-03	237	LDPE '4'	High temperature	High temperature	–
Liner-04	237	HDPE '2'	High temperature	High temperature	–
Liner-05	296	LDPE '4'	High temperature	High temperature	–
Liner-06	236	Vinyl acetate	High temperature	High temperature	–
Liner-07	227	'BPA FREE'	High temperature	High temperature	–
Liner-09	237	'BPA FREE'	High temperature	High temperature	–
Liner-10	200	See note	High temperature	High temperature	–

Note: PVC free, phthalate free, fabricated of polyester/polyethylene material.

Reusable drinking bottles

New PC reusable water bottles were purchased in Ottawa retail stores and used drinking bottles were donated by members of the Environmental Health Science and Research Bureau, Health Canada. Table 2 describes the bottles used in the study and the test applied. Five new PC drinking bottles were tested for BPA migration to water for 2, 8, 24, 96, and 240 h at 40°C; and for 24 h at 4°C. The migration test for BPA to water from ten used PC reusable drinking bottles was conducted for 24 h at 40°C. One used PC drinking bottle was placed in a refrigerator at 4°C for 24 h to confirm low BPA migration to water under refrigerated conditions.

Migration protocol

With the exception of the dishwashing test, all new baby bottles were used once and rinsed with HPLC-grade water three times before use. The weights of empty and simulant-filled bottles were recorded. After being filled with simulant (at room or high temperature), the bottles or liners were placed into an incubator at 40 or 60°C for the designated time to allow for the migration of BPA from the baby bottle material to the simulant. In order to test the migration at refrigerator conditions, PC drinking bottles filled with HPLC-grade water were placed in a refrigerator at 4°C for 24 h. At the end of each migration period, the bottles were removed from the incubator or the refrigerator and were allowed to reach room temperature for 2 h before the samples were pre-concentrated using SPE.

Water simulant sample preparation

Water simulant was spiked with ^{13}C-labelled BPA and loaded onto a preconditioned (water, methanol, acetone) Waters Oasis HLB (200 mg) SPE glass cartridge at approximately 5 ml min^{-1}. The SPE cartridge was then dried under water-aspirator vacuum and eluted with 5 ml of methanol followed by 5 ml of acetone. The extract was concentrated to dryness under a gentle stream of nitrogen and reconstituted with 70 µl of acetone. The sample was then derivatized for 10 min at 40°C using 30 µl of MSTFA and analysed by triple quadrupole GC-MS/MS.

Ethanol/water simulant sample preparation

A 10 ml aliquot of the ethanol/water simulant was spiked with ^{13}C-labelled BPA. The sample was then concentrated to 5 ml under nitrogen flow and acidified to pH 2 with 0.1% tetrafluoroacetic acid (TFA) in methanol. The sample was then loaded onto a preconditioned (water, methanol, acetone) Waters Oasis HLB (200 mg) SPE glass cartridge. The SPE cartridge was dried under water-aspirator vacuum and eluted with 10 ml 0.1% TFA in methanol. The extract was concentrated to dryness under a gentle stream of nitrogen and reconstituted with 70 µl of acetone. The sample was then derivatized for 10 min at 40°C using 30 µl of MSTFA and analysed by GC-MS/MS.

Polymer identification of non-PC baby bottles

The types of plastics used in the manufacture of the non-PC baby bottles tested for BPA were characterized by FTIR using attenuated total reflectance (ATR) in

Table 2. Bisphenol A (BPA) migration testing procedures applied to PC-reusable bottles.

Bottle brand	Size (ml)	Age and use	Migration testing method
New PC bottles			
PCB-01	500	New	24 h, 4°C; 2.5 h, 22°C; repeated use
PCB-02	400	New	24 h, 4°C; 2.5 h, 22°C; repeated use
PCB-03	500	New	24 h, 4°C; 2.5 h, 22°C; repeated use
PCB-04	800	New	24 h, 4°C; 2.5 h, 22°C; repeated use
PCB-05	650	New	24 h, 4°C; 2.5 h, 22°C; repeated use
Used PC bottles			
Used GB-02A	1000	Ten years, water	24 h, 40°C
Used GB-02B	500	Five years, water	24 h, 40°C
Used GB-02C	1000	Five years, water	24 h, 40°C
Used GB-02D	1000	Five years, water	24 h, 40°C
Used GB-02E	1000	Five years, water	24 h, 40°C
Used GB-02F	400	One year, water	24 h, 40°C
Used GB-02G	500	Five years, hot tea	24 h, 40°C
Used GB-04	600	Three years, water	24 h, 40°C
Used GB-05	550	One year, water	24 h, 4°C
Used GB-A	500	Three years, water	24 h, 40°C
Used GB-B	500	Six months, water	24 h, 40°C

accordance with the Product Safety Laboratory (PSL) method to identify unknown polymers and plasticizers by FTIR (PSL-Health Canada 2007). Polymer identification was conducted for 14 baby bottles by comparison of spectra with an industrial polymer spectral library.

Leachable lead and cadmium from glass bottles

The concentration of lead and cadmium from eight glass baby bottles was determined using the PSL's method for the determination of leachable lead and cadmium from glazed ceramics and glassware (PSL-Health Canada 2002).

GC/MS/MS analysis

The chromatographic separation of extracts was performed on a Zebron ZB-5HT capillary column (30 m × 0.25 mm × 0.1 µm) from Phenomenex (Torrance, CA, USA), using an Agilent 6890 gas chromatograph equipped with an autosampler (Agilent 7683B Series). A 1 µl sample was injected in splitless mode at 250°C. The GC oven temperature programme was as follows: 60°C (hold 1 min) to 280°C at 10°C min^{-1}, at a flow rate of 1 ml min^{-1} in constant flow mode.

Mass spectrometric experiments were performed using a Waters-Micromass Quattro micro triple quadrupole mass spectrometer (Waters Corp., Milford, MA, USA). The source and GC interface temperatures were set at 180 and 250°C, respectively. The MS/MS was operated in electronic impact at 70 eV in multiple reaction mode (MRM). MassLynx version 4 was used for data acquisition and processing. The following MRM transitions (*m/z*) were monitored: BPA (357 → 191) and ^{13}C-BPA (369 → 197).

Quality control and method performance

Included with each sample set was a 300 ml HPLC-grade water sample in order to correct for background contributions and inter-day variability. All samples were quantified using a ^{13}C-labelled BPA internal standard and a seven-point calibration curve. The method detection limit (MDL) was determined according to the EPA Regulation 40 CFR part 136 (Appendix B) method. Seven replicates of each food simulant spiked at 0.25 ng l^{-1} BPA were processed through the entire extraction procedure and analysis. The standard deviation associated with the analysis multiplied by a Student's *t*-test value of 3.143, appropriate for a 99% confidence level, provided the method detection limit. The limit of quantification (LOQ) was calculated as ten times the standard deviation associated with seven replicate analyses of BPA. The MDL and LOQ were 0.04 and 0.11 ng l^{-1}, respectively. The mean recovery was 93.22% (%RSD = 9.7, n = 7).

Results and discussion

Body temperature testing

We have conducted migration studies of BPA from baby bottles using a variety of testing conditions and food simulants. This study was designed to simulate repeated normal use, and to investigate the highest concentration levels that could potentially migrate from the material used to fabricate baby bottles and reusable PC drinking bottles. Glass baby bottles were not tested for BPA migration. In the first part of this work, 14 brands of PC baby bottles available in Canada were filled with two different simulants: water was used to simulate migration to aqueous and acidic foods, and a 50% ethanol/water solution was used to simulate migration to fatty foods such as infant formula (USFDA 2007). The bottles were incubated for 8, 24 or 240 h (10 days) at 40°C to simulate use at body temperature. The 10-day scenario was included to estimate migration from both repetitive use and worst-case scenarios. The material of two baby bottle samples was found to be non-PC. Therefore, only twelve PC baby bottles were included in the calculation of the average residual BPA, which ranged from 0.11 µg l^{-1} in water incubated for 8 h to 2.39 µg l^{-1} in the 50% ethanol simulant incubated for 240 h. The excluded non-PC baby bottles did not have detectable levels of BPA under the above experimental conditions. Unsaturated food oil is recognized as being the best simulant for fatty foods. However, due to the difficulty associated with the analysis of a migrant in such matrices, 50% ethanol was chosen as a reasonable simulant for fatty food. As can be seen in Table 3, the levels of BPA extracted into 50% ethanol food simulant were higher relative to the levels

Table 3. Average concentration (µg l^{-1}) of residual bisphenol A (BPA) leached from baby bottles using water and 50% ethanol as a food simulants.

Food simulant	8-h migration (40°C)	24-h migration (40°C)	240-h migration (40°C)
Water	0.11	0.12	1.88
50% Ethanol	0.17	1.52	2.39

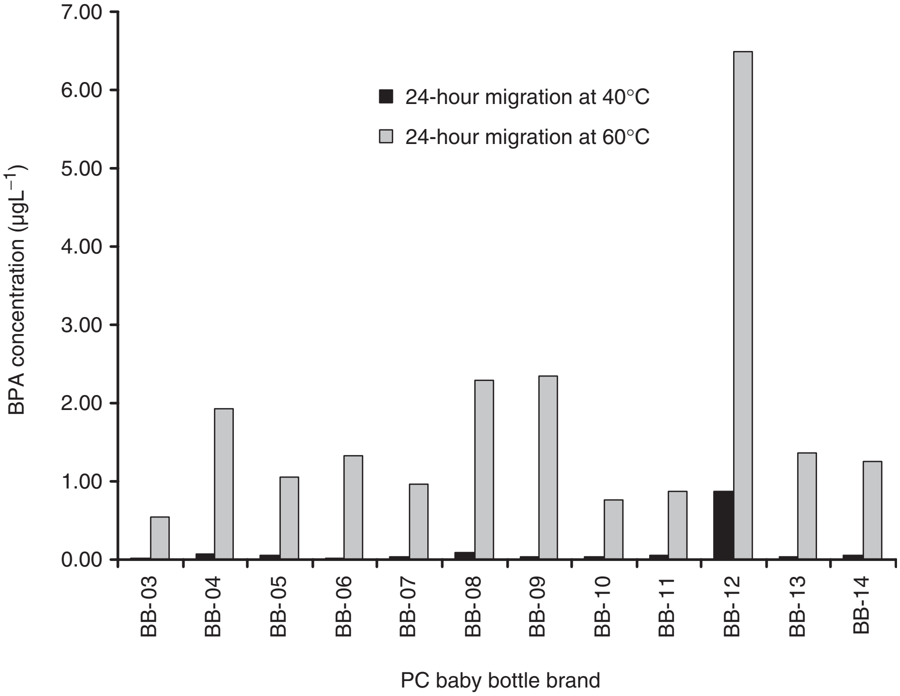

Figure 1. Comparison of bisphenol A (BPA) migration from polycarbonate baby bottles at 40°C and at 60°C using water as a food simulant.

extracted into water. This indicates that either the 'hot water ageing' effect resulting in the hydrolysis of the PC was higher when this simulant was used, or residual BPA remaining in contact with the polymer after processing was more readily released in the presence of the ethanol solution. Since directions for the preparation of infant formula typically specify that water be boiled for sterilization purposes and then cooled before pouring into the baby bottle, migration testing at 40°C best represents actual use. In a recent study, Maragou et al. (2008) assessed the migration of BPA from 31 new PC baby bottles under a variety of conditions that simulated actual use, including repeated cleaning of bottles in a dishwasher or use of a scrubbing brush. In their study, cleaned bottles were sterilized prior to being filled with water or 3% acetic acid (w/v) food simulants, and then incubated at 70°C for 2 h. The study confirmed that BPA migration to water was linked to temperature of the simulant: migration was observed when the baby bottles were filled with boiling water with incubation at room temperature for two h while no migration of BPA was observed with incubation at 70°C for 2 h. This study demonstrates that both temperature and time are critical factors in the increased BPA migration to water or ethanol/water simulants. In addition, it should be emphasized that our new analytical method combining BPA derivatization with MSTFA and analysis by GC-EI/MS/MS allowed the detection and the quantitation of BPA at trace levels, and made it possible to detect BPA migration at lower temperature.

High-temperature migration testing

In this experiment, baby bottles or baby bottle liners were filled with boiling water at 100°C, or with 10% ethanol at 85°C. The samples were then incubated at 60°C. Figure 1 shows a comparison of the levels of BPA leached from PC baby bottles tested for 24 h at 40°C and at higher temperature (60°C) using water as a food simulant. These results show unequivocally that the BPA migration from PC bottles significantly increased with the testing temperature, with an average concentration of 0.12 $\mu g\,l^{-1}$ at 40°C and 1.77 $\mu g\,l^{-1}$ at 60°C. These results are also in agreement with conclusions of other studies (Biles et al. 1997; Le et al. 2008; Maragou et al. 2008). In fact, it has been well documented that BPA migration increases with contact period and higher temperature, due, probably, to hydrolysis of PC polymer by 'hot water ageing' (Bair et al. 1979; Pryde et al. 1982; Narkis and Bell 1982; Joseph et al. 1982; Narkis et al. 1984). A recent study conducted by Ehlert et al. (2008) investigated the migration pattern of BPA into water during microwave heating of PC baby bottles. In that study, PC baby bottles were filled with water and heated to 100°C during three microwave cycles, and the migration of BPA into water ranged from <0.1 to 0.7 $\mu g\,l^{-1}$.

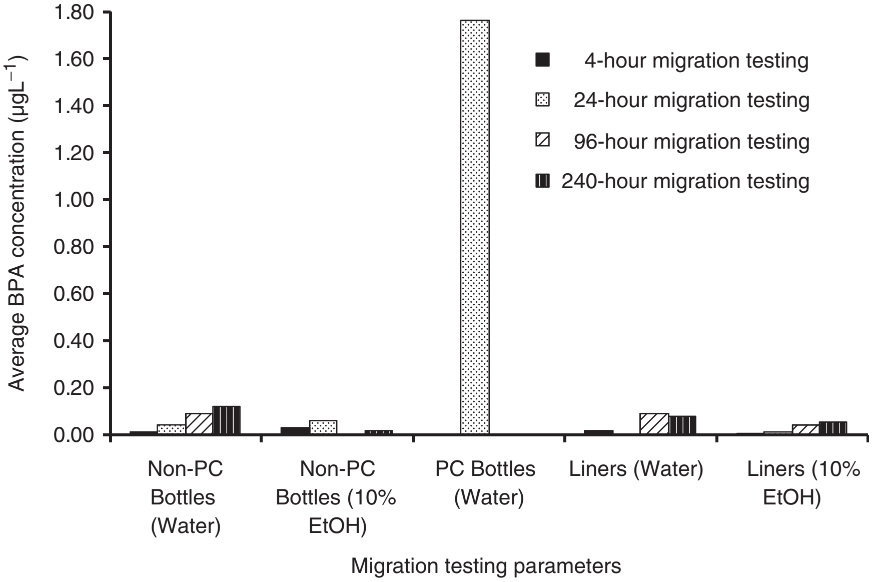

Figure 2. Comparison of BPA leached from PC baby bottles, non-PC baby bottles, and liners at 60°C. PC bottles were only tested for 24 h.

We applied the previously described high-temperature testing conditions to nine non-PC baby bottles (BB-01, BB-02, BB-17 to BB-23) and ten baby bottle liners (Liner-01 to Liner-10), using water and 10% ethanol as a food simulants. As shown in Figure 2, traces of BPA were detected in non-PC bottles and liners, but at extremely low levels compared with the relatively high concentrations extracted from PC bottles. It should be noted that PC baby bottles ($n = 2$) were tested for 24 h at high temperature, using water as a food simulant, for comparison purposes only. The average BPA concentration in non-PC baby bottles after 10 days at high temperature was similar to the levels found in PC bottles after 24 h at 40°C. This is a good indication that non-PC baby bottles may be considered as appropriate alternatives to PC bottles, in order to minimize exposure BPA from PC-plastic baby bottles.

Dishwashing

Figure 3 shows that BPA migration decreased abruptly after the second dishwashing, at which time the BPA concentration was 0.07 $\mu g\,l^{-1}$, and then remained constant at low level, around 0.01 $\mu g\,l^{-1}$, over the next four dishwashings. A repeated use migration study conducted by Biles et al. (1997) showed that residual BPA migrated from PC baby bottle material to 10% aqueous ethanol at 100°C for 30 min over four cycles of use. After an initial ‘bloom’, the concentration of BPA decreased rapidly and then levelled out. Another migration study of PC nursing bottles with water at 95°C for 30 min revealed a decrease in BPA migration by repeated elution (Kawamura et al. 1998), and similar conclusions were drawn by Sun et al. (2000), where BPA migration to hot water from baby bottles decreased five-fold between the first and the fourth migration cycles, using the same bottle. These results are in agreement with these studies. Biedermann-Brem et al. (2008) recently studied the effects of extreme washing conditions, such as the use of very strong alkali detergents at 80°C for 1 h, followed by drying of unrinsed bottles at 90°C for 30 min. After 30 washing cycles, the amount of BPA formed from the degradation of the PC ranged from 0.9 to 7.0 $\mu g\,l^{-1}$. Although base-catalysed hydrolysis of PC is favoured at high temperature (Thompson and Klemchuk 1996), in the present study the impact of dishwashing cycles on BPA migration was not significant, possibly because, in a domestic dishwasher, the recommended wash mixture is not a strong alkaline solution and any residual alkaline detergent is removed during the rinse cycle. In addition, the contact period may be too short to induce degradation of the bottle walls and the consequent increase in the accessibility of extractable residual BPA monomers.

BPA migration from reusable PC drinking bottles

The average BPA concentration obtained from new bottles (Figure 4) ranged from 0.01 to 2.16 $\mu g\,l^{-1}$ for migration testing with water conducted at 40°C for 2–240 h. These data agree with the results obtained by Le et al. (2008), in which the BPA released from PC bottles into water at room temperature was found to increase with time. However, contrary to the above study, this investigation revealed a significant difference between the levels of BPA migration from new

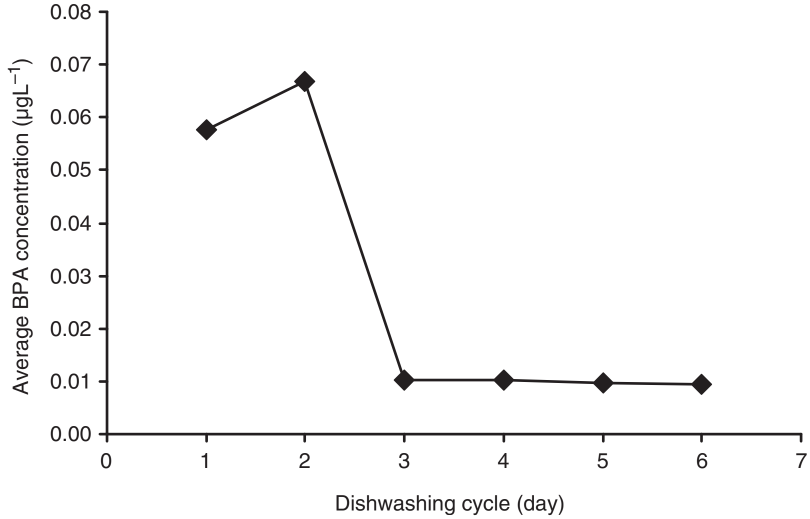

Figure 3. Repeated dishwashing study: average concentration of BPA ($\mu g\,l^{-1}$) leached from baby bottles ($n = 9$) using water as a food simulant.

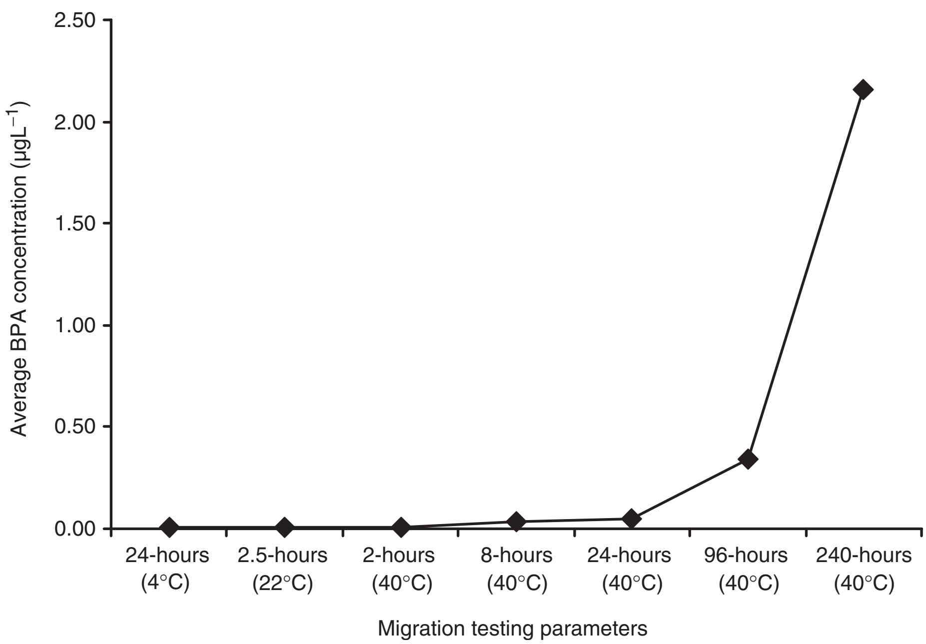

Figure 4. Average concentration of BPA ($\mu g\,l^{-1}$) leached from new PC drinking bottles ($n = 5$) using water as a food simulant.

and used PC drinking bottles; after 24-h migration testing at 40°C, the average BPA concentration from new and used PC drinking bottles was 0.01 and 0.20 $\mu g\,l^{-1}$, respectively. In a recent study (Cao and Corriveau 2008), the BPA leached from PC bottles ranged from 1.7 to 4.1 $\mu g\,l^{-1}$, when the baby and drinking bottles were filled to capacity with boiling water and then left at room temperature for 24 h. In our work, similar levels were observed for repeated normal use testing, after 240-h migration at 40°C, with a concentration range of 1.3–4.7 $\mu g\,l^{-1}$. As expected, the migration in both new and used PC bottles at 4°C was lower than that observed at higher temperature.

Simulant loss during the migration testing

To determine the loss of simulant during the incubation periods, for each temperature tested three baby bottles were filled with simulant, weighed, and then covered with aluminium foil secured with cotton twine. The bottles were then placed into an incubator that had been set to the required temperature. At chosen intervals the bottles were removed from the incubator and the weights recorded. Figure 5 shows that at 40°C less than 1% of the water had evaporated after 10 days. Under the same conditions, 2% of the 50% ethanol simulant had evaporated. This confirms that the BPA concentrations determined in the migration

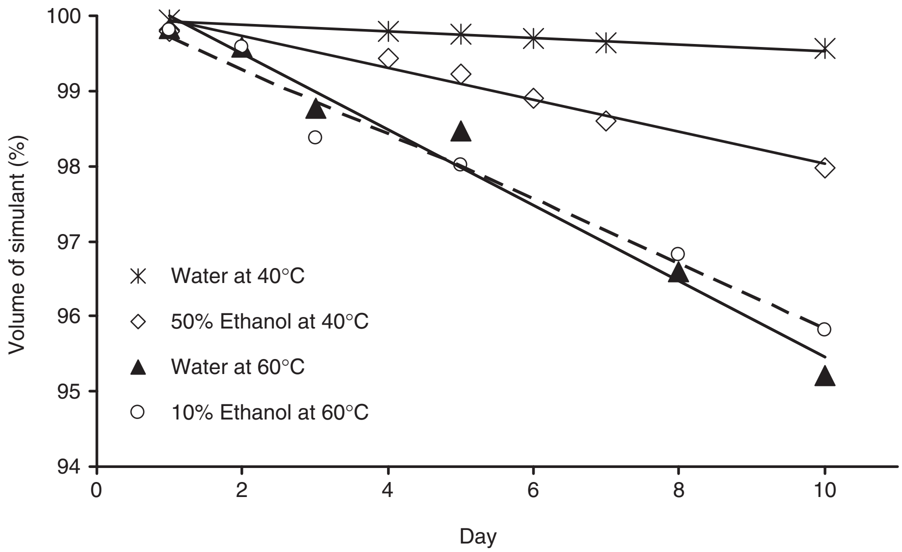

Figure 5. Loss of simulant from baby bottles in the incubator due to evaporation over 10-day migration testing.

experiments at 40°C were not significantly affected by evaporation of the food simulant. At 60°C, after the 10-day evaporation testing period, the loss from both water and the 10% ethanol solution was under 5%. However, the BPA migration concentrations were not adjusted for evaporative loss that occurred during the testing process.

Polymer identification of non-PC baby bottles

In all cases, results from FTIR testing confirmed that the 'BPA-free' baby bottles were not made from PC; they were made from polysulfone, polystyrene or polypropylene. Traces of BPA found to migrate from these bottles could be artefacts from the manufacturing process.

Determination of leachable lead and cadmium in glass bottle samples

The glass baby bottles, being free of BPA, were not tested for BPA leaching. However, as glass baby bottles may represent a safe alternative to PC baby bottles, they were subjected to a migration test for lead and cadmium prescribed under the Canadian Glazed Ceramics and Glassware Regulations of the Hazardous Products Act. These Regulations apply to all products that are to be used or that may be used in storing, preparing or serving food and that are covered with a coating, glaze or decoration which may contain lead or cadmium. The Regulations establish migration limits for these metals when filled with a 4% by volume acetic acid solution and stored at room temperature for 24 h. The glass baby bottles tested in accordance with these Regulations had no detectable levels of lead or cadmium.

Conclusions

Combining solid-phase extraction, derivatization and GC/EI-MS/MS analysis proved to be a suitable analytical method for trace-level detection and quantification of BPA leaching from PC baby bottles and reusable PC drinking bottles. This work confirmed and extended previous studies on the migration of BPA from PC baby bottles. A higher temperature and longer testing period resulted in higher BPA migration from PC bottles. Compared with the levels of BPA that migrated from PC baby bottles, migration tests conducted at high temperature revealed that non-PC baby bottles and baby bottle liners contain only trace levels of BPA. While use of glass baby bottles seems to be a good alternative to PC plastic bottles when used with appropriate precautions to prevent risks to children, from a BPA perspective, plastic baby bottles made of polysulfone, polystyrene or polypropylene are also reasonable alternatives. Regarding reusable PC drinking bottles, use with cold beverages for a short period of time would result in a lower migration rate of BPA than use with beverages at higher temperatures or over longer periods of time.

Acknowledgements

The authors gratefully acknowledge financial and material support from the Product Safety Directorate (Health Canada).

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