

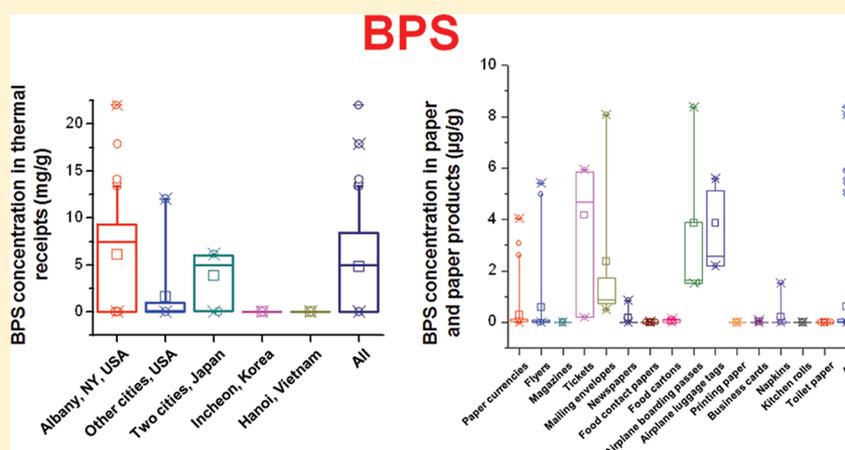
Bisphenol S, a New Bisphenol Analogue, in Paper Products and Currency Bills and Its Association with Bisphenol A Residues

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S Supporting Information



ABSTRACT: As the evidence of the toxic effects of bisphenol A (BPA) grows, its application in commercial products is gradually being replaced with other related compounds, such as bisphenol S (BPS). Nevertheless, very little is known about the occurrence of BPS in the environment. In this study, BPS was analyzed in 16 types of paper and paper products ($n = 268$), including thermal receipts, paper currencies, flyers, magazines, newspapers, food contact papers, airplane luggage tags, printing paper, kitchen rolls (i.e., paper towels), and toilet paper. All thermal receipt paper samples ($n = 111$) contained BPS at concentrations ranging from 0.0000138 to 22.0 mg/g (geometric mean: 0.181 mg/g). The overall mean concentrations of BPS in thermal receipt papers were similar to the concentrations reported earlier for BPA in the same set of samples. A significant negative correlation existed between BPS and BPA concentrations in thermal receipt paper samples ($r = -0.55$, $p < 0.0001$). BPS was detected in 87% of currency bill samples ($n = 52$) from 21 countries, at concentrations ranging from below the limit of quantification (LOQ) to 6.26 $\mu\text{g/g}$ (geometric mean: 0.029 $\mu\text{g/g}$). BPS also was found in 14 other paper product types ($n = 105$), at concentrations ranging from <LOQ to 8.38 $\mu\text{g/g}$ (geometric mean: 0.0036 $\mu\text{g/g}$; detection rate: 52%). The estimated daily intake (EDI) of BPS, through dermal absorption via handling of papers and currency bills, was estimated on the basis of concentrations and frequencies of the handling of papers by humans. The median and 95th percentile EDI values, respectively, were 4.18 and 11.0 ng/kg body weight (bw)/day for the general population and 312 and 821 ng/kg bw/day for occupationally exposed individuals. Among the paper types analyzed, thermal receipt papers were found to be the major sources of human exposure to BPS (>88%). To our knowledge, this is the first report on the occurrence of BPS in paper products and currency bills.

INTRODUCTION

Bisphenol A (BPA) has been used in a wide variety of commercial applications worldwide for several decades.^{1–4} Humans are exposed to BPA due to the leaching of this compound from polycarbonate plastics or epoxy-lined food and drink containers.^{1,3} BPA can act as a weak estrogen receptor agonist and has been implicated in a wide variety of adverse health outcomes, especially reproduction and development, in

laboratory animals.^{1–4} Considerable controversy surrounds the low-dose toxicity of BPA and widespread exposure of humans to this compound.¹ The United States Environmental

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Protection Agency (USEPA) and the European Food Safety Authority (EFSA) established an oral reference dose (RfD) for BPA of 50 $\mu\text{g}/\text{kg}$ body weight (bw)/day.^{5,6} Health Canada established a provisional tolerable daily intake (TDI) at 25 μg BPA/kg bw/day.⁷ Further, the European Commission established a migration limit of 600 $\mu\text{g}/\text{kg}$ for BPA in plastic products that are intended for food-contact applications.⁸ To comply with restrictions and regulations, manufacturers are gradually replacing BPA with other related compounds, including bisphenol S (BPS; 4,4'-sulfonyldiphenol), as substitutes in industrial applications.⁹ BPS is also used as an anticorrosive agent in epoxy glues and as a reagent in polymer reactions.¹⁰ BPS has been reported to occur in canned foodstuffs at concentrations on the order of several tens of nanograms per gram.¹⁰

Thermal papers containing BPA as a color developer are produced in massive quantities for many daily applications, including cash register receipts, luggage tags, books, faxes, and labels.^{11,12} Extremely high levels of BPA (up to 3–22 g/kg) have been reported to occur in thermal receipt papers.^{11–13} Several thermal paper producers have started replacing BPA with other substitutes; BPS has been suggested as a substitute for BPA. For example, Japan phased out BPA in thermal receipt papers in 2001, and a major manufacturer of thermal receipt papers in the USA reported replacement of BPA with BPS.^{14–16} The European Commission estimates that ~30% of thermal papers enter the paper recycling streams.¹⁷ Many paper products, such as advertisement brochures (flyers), tickets, mailing envelopes, newspapers, napkins (facial tissue), kitchen rolls (paper towels), toilet paper, and food cartons (pizza paperboards, food buckets, and snack food boxes) are made from recycled paper.^{18–21} It is expected that the recycling of thermal paper can introduce BPS into the cycle of paper production and cause BPS contamination of these paper products.¹⁹ Given that most people come into contact with thermal receipt papers and paper products on a daily basis, exposure of humans to BPS through dermal contact is inevitable.²⁰ Studies have shown that many bisphenol analogues, such as BPS, bisphenol F (BPF; 4,4'-dihydroxydiphenylmethane), bisphenol AF [BPAF; 4,4'-(hexafluoroisopropylidene)diphenol], and bisphenol B [BPB; 2,2-bis(4-hydroxyphenyl)butane] possess genotoxicity and estrogenic activity similar to that of BPA.^{9,22–28} A recent study showed that BPB and BPAF can activate the human pregnane X receptor (PXR), a nuclear receptor that functions as a regulator of xenobiotic metabolism.²⁹ Another study from Japan indicated that some BPA substitutes such as BPF and BPS appear to be more resistant to environmental degradation as compared to BPA.³⁰ Considering the toxic potential of BPS, studies are needed to investigate the occurrence, fate, and effects of this compound in the environment and in human populations.

Our previous studies have reported the widespread occurrence of BPA in several types of paper products, at nanogram-per-gram to milligram-per-gram concentrations.^{31,32} In this study, we determined BPS concentrations in 268 samples, representing 16 types of paper products, with the aim of establishing baseline concentrations of this compound in paper products. On the basis of measured concentrations, potential human exposure doses to BPS from the handling of papers were estimated. This is the first study to describe the occurrence of BPS in paper products and to estimate exposure doses in humans.

MATERIALS AND METHODS

Sample Collection. Thermal receipt paper samples ($n = 111$) were collected from four countries, the USA, Japan, Korea, and Vietnam, in 2010 and 2011. The thermal receipts ($n = 81$) from the USA were collected from 58 locations, including supermarkets, grocery stores, banks, public libraries, gas stations, and restaurants in Albany, New York City, and Buffalo (New York), Boston (Massachusetts), Chicago (Illinois), Weston (Vermont), and Charlotte (North Carolina). Thermal receipt samples ($n = 30$) were also collected from retail stores in Matsuyama and Tokyo (Japan), Incheon (Korea), and Hanoi (Vietnam). Currency bill samples ($n = 52$) were collected from the USA, Canada, Czech Republic, Russia, Turkey, Australia, Brazil, Egypt, South Africa, China, India, Japan, Korea, Kuwait, Malaysia, Philippines, Singapore, Thailand, Vietnam, and United Arab Emirates (UAE), from March 2010 to January 2011. Paper currencies (expected to be in circulation) were purchased mainly from currency exchange stands in international airports in the USA, Japan, and Korea. Currency information, including name, value, serial number, dimensions, and the release date, are summarized in Table S1 (Supporting Information). Other paper products ($n = 105$) were collected mainly in Albany (New York), with a few samples from New York City and Buffalo (New York) and Boston (Massachusetts), in 2010 and 2011. These samples were grouped into 14 categories: flyers (e.g., advertisement brochures, store coupons, gift cards, bus schedule), magazines, tickets (e.g., train and bus tickets), mailing envelopes, newspapers, food contact papers (e.g., fast-food wrappers, paper cups, paper plates), food cartons (e.g., pizza paperboards, food buckets, snack food boxes), airplane boarding passes, airplane luggage tags, printing paper (i.e., regular copy paper), business cards, facial tissue (referred to as napkins in this study), kitchen rolls (paper towels), and toilet paper. Samples were individually wrapped in polyethylene bags and stored at $-20\text{ }^{\circ}\text{C}$ until further analysis.

Sample Preparation. Samples were extracted and analyzed for BPS, as described earlier.^{31,32} For thermal receipt papers, a circular spot (diameter: 19 mm) was taken in the middle of each receipt using a punch (Uchida Corp., Torrance, CA). After weighing, each spot was cut into small pieces, transferred into a 15 mL polypropylene conical tube (PP tube), and extracted by shaking with 5 mL of methanol (HPLC grade, J.T. Baker, Phillipsburg, NJ). The mixture was centrifuged at $4500 \times g$ for 3 min (Eppendorf Centrifuge 5804, Hamburg, Germany), and the extract was transferred into a new PP tube. The extraction was repeated two more times with 3.5 mL of methanol. The extracts were combined and concentrated to 10 mL under a gentle nitrogen stream. An aliquot of the extract was serially diluted to 1:2000 in methanol and spiked with 5 ng of $^{13}\text{C}_{12}$ -bisphenol A ($^{13}\text{C}_{12}$ -BPA, 99%; Cambridge Isotope Laboratories, Andover, MA), as an internal standard, before being subjected to high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS) analysis.

For paper currencies, three circular spots (diameter: 19 mm) were taken from three portions of each paper currency: the lower left corner (denoted as LLC), middle (M), and upper right corner (URC), as described earlier.³¹ The lower left and upper right corners are presumed to be frequently rubbed or pulled, while the middle region is presumed to be touched relatively less often. After weighing, spots were cut into small pieces, spiked with 20 ng of $^{13}\text{C}_{12}$ -BPA, and extracted three times with methanol as described above. The extracts were

Table 1. Concentrations of Bisphenol S (BPS) in Thermal Receipt Papers (mg/g) From the USA, Japan, Korea, and Vietnam and in Other Types of Papers ($\mu\text{g/g}$) from Albany, New York, USA

site	<i>n</i> ^a	BPS Concentration in Thermal Receipt Papers (mg/g)					range	detection rate (%)
		GM ^b	fifth percentile	median	95th percentile			
Albany, USA	81	0.443	0.0003	7.44	13.4	0.0000138–22.0	100	
other cities, USA	10	0.196	0.0133	0.414	7.11	0.000998–12.0	100	
Japan	6	0.624	0.0248	5.50	6.10	0.000546–6.13	100	
Korea	11	0.0007	0.0001	0.0008	0.0088	0.0000896–0.011	100	
Vietnam	3	0.0003	0.0001	0.0003	0.0005	0.000105–0.000554	100	
all thermal receipt papers	111	0.181	0.0002	5.00	13.2	0.0000138–22.0	100	
paper type	<i>n</i>	BPS Concentration in Several Paper Products ($\mu\text{g/g}$)					range	detection rate (%)
		GM	fifth percentile	median	95th percentile			
paper currencies	52	0.0290	0.0003	0.0301	1.86	<LOQ ^c –4.04	94	
flyers	30	0.0099	0.0001	0.0109	4.69	<LOQ–5.41	80	
magazines	5	0.0003	0.0001	0.0001	0.0039	<LOQ–0.0045	40	
tickets	4	2.33	0.858	5.27	5.92	0.183–5.93	100	
mailing envelopes	5	1.33	0.527	0.870	6.81	0.476–8.08	100	
newspapers	8	0.0007	0.0001	0.0001	0.753	<LOQ–0.840	25	
food contact papers	12	0.0001	0.0001	0.0001	0.0053	<LOQ–0.0117	8.3	
food cartons	7	0.0048	0.0001	0.0922	0.136	<LOQ–0.143	57	
airplane boarding passes	4	3.00	1.53	2.76	7.71	1.51–8.38	100	
airplane luggage tags	4	3.56	2.25	3.84	5.51	2.19–5.58	100	
printing paper ^d	3	0.0001	0.0001	0.0001	0.0001	<LOQ	0	
business cards	6	0.0005	0.0001	0.0001	0.0561	<LOQ–0.0730	33	
napkins	8	0.0004	0.0001	0.0001	0.992	<LOQ–1.53	25	
kitchen rolls (paper towels) ^d	3	0.0001	0.0001	0.0001	0.0001	<LOQ	0	
toilet paper	6	0.0001	0.0001	0.0001	0.0007	<LOQ–0.0009	17	
all papers	157	0.0072	0.0001	0.0085	4.75	<LOQ–8.38	66	

^a*n*: number of samples. ^bGM: geometric mean. ^cLOQ: 0.1 ng/g. ^d: not detectable.

concentrated to 10 mL, and 1 mL of the aliquot was transferred into a gas chromatographic (GC) vial for HPLC-MS/MS analysis.

For other paper products, a circular 19 mm diameter spot was taken and cut into small pieces. Five nanograms of ¹³C₁₂-BPA were added as an internal standard prior to extraction, and the sample was extracted three times with methanol, as described above. The final extract was passed through a 0.2- μm nylon filter (Phenomenex, Torrance, CA), transferred into a GC vial, and analyzed by HPLC-MS/MS.

Instrumental Analysis. Identification and quantification of BPS was performed with an Applied Biosystems API 5500 electrospray triple quadrupole mass spectrometer (ESI-MS/MS; Applied Biosystems, Foster City, CA) coupled with an Agilent 1100 Series HPLC system (Agilent Technologies Inc., Santa Clara, CA), equipped with a binary pump and an autosampler. Chromatographic separation was carried out by a column (Betasil C18, 100 \times 2.1 mm; Thermo Electron Corporation, Waltham, MA), connected in series with a Javelin guard column (Betasil C18, 20 \times 2.1 mm; Thermo Electron Corporation). The mobile phase flow rate was 300 $\mu\text{L}/\text{min}$, and the injection volume was 10 μL . During the mobile phase, methanol and milli-Q water (purified by an ultrapure water system; Barnstead International, Dubuque, IA), at a gradient starting with 15% methanol at 0 min, was held for 2 min; increased to 90% methanol at 2 to 9 min; then increased to 99% methanol at 9 to 12 min, held for 3 min; and finally reversed to 15% methanol, held for 5 min before the next injection. The negative ion multiple reaction monitoring (MRM) mode was used, and the MRM transitions monitored were 249 > 108 for BPS (98%; Sigma-Aldrich, St. Louis, MO)

and 239 > 224 for ¹³C₁₂-BPA. Nitrogen was used both as a curtain and a collision gas. Cone voltage was -30 V, and collision energy was 22 V. Capillary voltage was kept at -4.5 kV, and desolvation temperature was 700 $^{\circ}\text{C}$.

Quality Assurance and Quality Control (QA/QC). With each set of 20 samples, a procedural blank, a spiked blank, a pair of matrix spiked samples, and duplicate samples were analyzed. The procedural blank, containing milli-Q water in place of the paper sample, was analyzed as a check for interferences or laboratory contamination. Trace levels of BPS (approximately 0.007 ng/mL) were found in procedural blanks in some batches, and background subtraction was performed in the quantification of concentrations in samples. The recoveries of BPS from spiked blanks and spiked matrices were 97 \pm 13% and 99 \pm 14% (mean \pm SD), respectively. The relative standard deviation (RSD) of replicate analysis of samples was <10%. Ten thermal receipt samples, 10 paper currency bills, and 10 samples from other paper types were randomly selected, and a fourth extraction was conducted with 3 mL of methanol (after the first three extractions) to confirm extraction efficiency of BPS from paper samples. BPS was detected in the fourth extraction (34 and 44 ng/mL; 3 mL in total) in two thermal receipt samples. In comparison with the extremely high concentrations (6.85 and 8.04 mg/g; in weight: 0.0190 and 0.0211 g, respectively) of BPS detected in the original thermal receipt samples, the residual BPS found in the fourth extraction was 0.08% of the total amount. For paper currency and other paper types, BPS was not detected in the fourth extraction. Instrumental drift in sensitivity was checked by analyzing a midpoint calibration standard after every 20 samples. To check for carryover of BPS from sample to sample, a pure solvent

(methanol) was injected after every 10 samples. The limit of quantification (LOQ) of BPS was 0.1 ng/g; quantification was by isotope-dilution method. Instrumental calibration was verified by injecting calibration standards ($n = 10$), ranging in concentrations from 0.01 to 100 ng/mL, and the regression coefficient (r) of the calibration curve, which was >0.99 . Because thermal receipt papers contained high concentrations of BPS, these samples were stored and analyzed in separate batches from other paper types and were diluted up to 20,000-fold.

Estimation of Daily Intake. There is no information on the transfer rates of BPS from paper products to human skin through handling of paper products. Therefore, values reported for BPA were used in the calculations.^{31,32} The estimated daily intake (EDI; ng/day) of BPS was calculated using eq 1

$$EDI = k \times C \times HF \times HT \times AF/10^6 \quad (1)$$

where k is the paper-to-skin transfer coefficient for BPS (21522.4 ng/s), a value reported for BPA from thermal receipt paper to human skin;¹³ C is the concentration of BPS in paper samples ($\mu\text{g/g}$); HF is the handling frequency (times/day; because the frequency of use and handling time are probably different, we assumed different frequency rates for various paper types; for thermal receipt paper, 2 and 150 times/day for the general population and occupationally exposed individuals, respectively; for paper currency, 2 and 20 times/day for the general population and occupationally exposed individuals; for other paper types, 5 times/day for flyers, tickets, mailing envelopes, food contact paper, food cartons, airplane boarding pass, airplane luggage tags, printing paper, and business cards and 10 times/day for magazines, newspapers, napkins, paper towels, and toilet paper for both the general population and occupationally exposed individuals); HT is the handling time of paper and is assumed to be 5 s for each handling; and AF is the absorption fraction of BPS by skin (27%), as reported in the literature.¹³ For example, if the median BPS concentration in thermal receipt is 5.0028 mg/g (= 5002.8 $\mu\text{g/g}$), the estimated median daily intake of BPS from handling of thermal receipts by the occupationally exposed individual can be calculated as

$$\begin{aligned} EDI &= 21522.4 \text{ ng/s} \times 5002.8 \text{ } \mu\text{g/g} \times 150 \text{ times/day} \\ &\quad \times 5 \text{ s/time} \times 27\%/10^6 \\ &= 21.5224 \text{ ng/s} \times 5.0028 \times 150 \text{ times/day} \times 5 \\ &\quad \text{s/time} \times 27\% \\ &= 21804 \text{ ng/day} \end{aligned}$$

Data Analysis. Data acquisition was accomplished with the Analyst 1.5.1 software package (Applied Biosystems). Statistical analysis was performed with Origin 7.5 (OriginLab Corporation, Northampton, MA). Concentrations below the LOQ were substituted with a value equal to the LOQ divided by the square root of 2 for the calculation of geometric mean (GM). Statistical differences between groups were tested by a one-way ANOVA with the Tukey test. The value of $p < 0.05$ was considered significantly different.

RESULTS AND DISCUSSION

Thermal Receipt Papers. BPS was detected in all thermal receipt paper samples ($n = 111$) at concentrations ranging from 0.0000138 to 22.0 mg/g (GM: 0.181 mg/g; Table 1). The highest geometric mean concentration of BPS (GM: 0.624 mg/g)

was found in thermal receipts collected from Japan, which was similar to that found in Albany, New York (GM: 0.443 mg/g; $p > 0.05$, one-way ANOVA). These values were slightly higher than those (GM: 0.196 mg/g; $p > 0.05$) in samples collected from other cities in the USA and significantly higher than the concentrations found in samples from Incheon, Korea (GM: 0.0007 mg/g; $p < 0.001$) and Hanoi, Vietnam (GM: 0.0003 mg/g; $p < 0.05$). There was no significant difference in the concentrations of BPS in thermal receipt papers from Korea and Vietnam (Table 1; $p > 0.05$).

BPS has been used as a substitute for BPA in thermal papers in recent years.^{9,14–16} Our previous study found high concentrations of BPA, ranging from <LOQ (1 ng/g) to 13.9 mg/g (GM: 0.211 mg/g), in most of the thermal receipt paper samples ($n = 103$, detection rate: 94%) collected from the USA, Japan, Korea, and Vietnam.³² The thermal receipt samples were further analyzed, along with a few additional samples ($n = 111$), for BPS in the present study. As shown in Table 1, the concentrations of BPS (GM: 0.181 mg/g; range: 0.0000138–22.0 mg/g; detection rate: 100%) in these samples were similar to the concentrations of BPA (GM: 0.211 mg/g). Interestingly, a significant negative correlation was found between BPS and BPA concentrations in thermal receipt samples ($n = 103$) (Figure 1; $r = -0.55$, $p < 0.0001$). In other words, the thermal

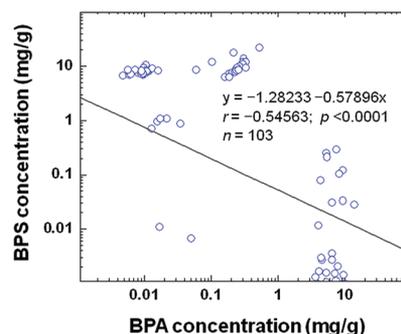


Figure 1. Negative correlation between BPS and BPA concentrations in thermal receipt papers ($n = 103$).

register receipts that contained high concentrations of BPS (at milligram-per-gram level) had low (at nanogram-per-gram level) or nondetectable concentrations of BPA and vice versa. The thermal receipt samples from Japan contained very high concentrations of BPS (GM: 0.624 mg/g), but BPA was not detected in these samples.³² This finding is consistent with the phase-out of BPA usage in thermal receipt papers in Japan in 2001.¹⁴ Recently, BPA also has been replaced with BPS in thermal receipt papers from the USA,^{15,16} which supports the widespread occurrence of BPS (GM: 0.405 mg/g; detection rate: 100%) in thermal receipt samples collected in the USA (Table 1). Nevertheless, the analogues of BPA should be evaluated for environmental persistence, bioaccumulation, and toxicity.^{9,26,29,30}

Five circular spots (diameter: 19 mm) were taken from each of five randomly selected receipts, namely upper left corner (ULC), lower left corner (LLC), middle (M), upper right corner (URC), and lower right corner (LRC), for the comparison of BPS concentrations in several portions of thermal receipt samples. There were no significant differences in the concentrations of BPS found among the five spots taken within each receipt paper (Figure S1 in the Supporting Information; $p > 0.05$).

Table 2. Estimated Daily Intake (ng/day) of BPS, via Handling of Papers, through Dermal Exposures, by the General Population and Occupationally-Exposed Individuals

paper type	general population				occupational exposure			
	GM	fifth percentile	median	95th percentile	GM	fifth percentile	median	95th percentile
thermal receipts	10.5	0.0107	291	767	787	0.802	21804	57493
paper currencies	0.0017	0.00001	0.0017	0.108	0.0168	0.0001	0.0175	1.08
flyers	0.0014	0.00001	0.0016	0.682	0.0014	0.00001	0.0016	0.682
magazines	0.0001	0.00002	0.00002	0.0011	0.0001	0.00002	0.00002	0.0011
tickets	0.339	0.125	0.766	0.860	0.339	0.125	0.766	0.860
mailing envelopes	0.194	0.0765	0.126	0.989	0.194	0.0765	0.126	0.989
newspapers	0.0002	0.00002	0.00002	0.219	0.0002	0.00002	0.00002	0.219
food contact papers	0.00002	0.00001	0.00001	0.0008	0.00002	0.00001	0.00001	0.0008
food cartons	0.0007	0.00001	0.0134	0.0198	0.0007	0.00001	0.0134	0.0198
airplane boarding passes	0.435	0.223	0.401	1.12	0.435	0.223	0.401	1.12
airplane luggage tags	0.518	0.327	0.559	0.800	0.518	0.327	0.559	0.800
printing paper	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
business cards	0.00007	0.00001	0.00001	0.0081	0.00007	0.00001	0.00001	0.0081
napkins	0.0001	0.00002	0.00002	0.288	0.0001	0.00002	0.00002	0.288
kitchen rolls (paper towels)	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002
toilet paper	0.00003	0.00002	0.00002	0.0002	0.00003	0.00002	0.00002	0.0002
total exposure (\sum EDI) ^a	12.0	0.762	293	772	789	1.55	21806	57499
exposure percentage from receipt (%)	87.6	1.40	99.4	99.3	99.8	51.6	100.0	100.0

^aRounded values.

Paper Currencies. BPA has been reported to migrate easily from thermal receipt papers to other objects because it is applied as a powdery film (i.e., not chemically bound).^{11,13} Direct thermal printing is the process whereby an image (text or graphics) is produced on the thermal paper by using an array of thermal heads.³³ The thermal paper typically consists of a base paper (a standard paper formulation) upon which is a thermal sensitive layer. The thermal sensitive layer typically consists of three components: the thermochromic dye, a weakly acidic color developer, and a solvent (generally a long-chain aliphatic compound such as fatty acid, amide, or alcohol). The most widely used color developer is BPA since it is cheap and readily available.³³ When the thermal sensitive layer is heated above the melting point of the solvent by a thermal head, BPA (the developer) interacts with the thermochromic dye, donating protons which open the rings of the dye and increase the conjugation of the system, resulting in a color/image.¹¹ Because BPS is structurally similar to BPA, it is presumed that BPS can easily migrate to other objects with which it comes in contact. Therefore, BPS can migrate from thermal receipts to paper currencies every time a receipt is placed near the currency in a cash register or wallet. In this study, three separate 19 mm spots taken on the paper currencies, namely LLC, M, and URC, were analyzed. BPS was found in 136 of 156 (87%) currency bill samples, representing 52 paper currencies from 21 countries, at concentrations ranging from <LOQ to 6.26 $\mu\text{g/g}$ (Table S1; Supporting Information). The highest BPS concentration, 6.26 $\mu\text{g/g}$, was found in the middle portion of a currency bill collected from Japan (Table S1; Supporting Information). Among the three different spots analyzed, BPS concentrations in the middle portion of the currencies (mean \pm SD; 0.41 \pm 1.16 $\mu\text{g/g}$) were relatively higher, in comparison with those found in the LLC and URC (0.26 \pm 0.80 $\mu\text{g/g}$ and 0.22 \pm 0.54 $\mu\text{g/g}$, respectively; $p > 0.05$). This might be explained by the fact that (1) the peripheral portions of paper currency are frequently handled by humans (i.e., frequent transfer of BPS from currency to finger) and (2) the middle portion of currency bill is likely to be in frequent contact with

small thermal receipts.^{12,13} We also have reported the concentrations of BPS in currency bills on the basis of area (Table S1; Supporting Information).

BPS concentrations in all three punches of currency bills from each country were averaged, as shown in Figure S2 (Supporting Information). The highest concentration of BPS (mean \pm SD; 4.04 \pm 2.46 $\mu\text{g/g}$) was found in paper currencies from Japan, followed by currencies from the USA (1.32 \pm 1.48 $\mu\text{g/g}$), Singapore (0.48 \pm 0.59 $\mu\text{g/g}$), Australia (0.22 \pm 0.05 $\mu\text{g/g}$), and Brazil (0.20 \pm 0.23 $\mu\text{g/g}$). BPS was not found in currencies from Egypt, South Africa, or the UAE (Table S1 and Figure S2; Supporting Information).

Our previous study showed that the transfer of BPA from thermal receipt paper to currency bills is a major source of BPA in paper currency.³¹ Considering that the concentration of BPS (GM: 0.181 mg/g; Table 1) is comparable to that of BPA in thermal receipt papers, it is expected that thermal receipt paper is a major source of BPS in paper currency. Our results suggest that the overall concentration of BPS (GM: 0.029 $\mu\text{g/g}$; median: 0.030 $\mu\text{g/g}$; Tables 1 and S1; Supporting Information) in paper currency samples was 1 order of magnitude lower than the concentration reported previously for BPA (GM: 0.853 $\mu\text{g/g}$; median: 1.13 $\mu\text{g/g}$).³¹ This might suggest that, although BPA has been gradually replaced with BPS in thermal receipt papers, BPS is still less prevalent in applications, which might explain the relatively low concentration of BPS in paper currency samples.

Other Paper Products. As stated above, it is expected that BPS, like BPA, is likely transferred from thermal receipt papers to other objects, including various types of papers.^{11,13} Recycling of thermal receipt papers together with other papers can cause cross-contamination of BPS in recycled papers.¹⁷ A wide range of paper products, including toilet paper, paper towels, newspapers, food cartons, and cardboard boxes, are made from recycled papers.^{18–21} Therefore, BPS can be expected to occur in various types of papers. In this study, 14 other types of paper products were analyzed for BPS. The overall BPS concentrations in the 105 paper samples,

representing 14 paper products (except for paper currency), ranged from <LOQ to 8.38 $\mu\text{g/g}$ (GM: 0.0036 $\mu\text{g/g}$; detection rate: 52%). BPS was found in 100% of tickets, mailing envelopes, airplane boarding passes, and airplane luggage tags (Table 1). BPS was frequently detected in flyers (advertisement brochures, store coupons, gift cards, and bus schedules) and food cartons (pizza paperboards, food buckets, and snack food boxes), with a detection rate of 80% and 57%, respectively. Printing paper and kitchen rolls did not contain BPS (Table 1). BPS concentrations in paper products (GM: 0.0072 $\mu\text{g/g}$, including paper currency) were 4–6 orders of magnitude lower than those (GM: 0.181 mg/g) in thermal receipt papers (Table 1). Widespread occurrence of BPS in paper products suggests that exposure of humans to BPS via handling of paper products is ubiquitous.

The highest concentration of BPS was found in airplane luggage tags (GM: 3.56 $\mu\text{g/g}$; range: 2.19–5.58 $\mu\text{g/g}$), followed by airplane boarding passes (3.00 $\mu\text{g/g}$; 1.51–8.38 $\mu\text{g/g}$), tickets (2.33 $\mu\text{g/g}$; 0.183–5.93 $\mu\text{g/g}$), and mailing envelopes (1.33 $\mu\text{g/g}$; 0.476–8.08 $\mu\text{g/g}$). BPS concentrations in these four types of samples were 2–4 orders of magnitude higher than the concentrations found in other types of papers, especially food-contact papers (GM: 0.0001 $\mu\text{g/g}$; range: <LOQ–0.0117 $\mu\text{g/g}$) and toilet paper (0.0001 $\mu\text{g/g}$; <LOQ–0.0009 $\mu\text{g/g}$) (Table 1; $p < 0.05$). One possible explanation is that these types of papers, including the airplane luggage tags, airplane boarding passes, and tickets are probably printed with a similar thermal printing process to that used in thermal receipts, which might account for the relatively higher concentrations in these types of papers compared to other papers. The European Commission estimates that ~30% of thermal papers enter recycling streams of municipal waste-paper.¹⁷ Thus, the concentrations of BPS in paper products also depend on the proportion of waste papers introduced into the paper production process.^{18–20} The concentrations of BPS in paper products (GM: 0.0036 $\mu\text{g/g}$, excluding paper currency) were slightly lower than those of BPA (0.0160 $\mu\text{g/g}$) in the same set of samples.³²

Daily Intake of BPS via Handling of Papers. Human exposure to BPS through dermal absorption, from handling of paper and paper products, is summarized in Table 2. The estimated fifth percentile, median, and 95th percentile values for daily intakes of BPS via handling of thermal receipt papers were 0.011, 291, and 765 ng/day for the general population and 0.802, 21804, and 57493 ng/day for occupationally exposed individuals, respectively. The daily BPS intakes via handling of paper currencies (calculated from fifth percentile, median, and 95th percentile concentrations) by the general population were estimated at 0.00001, 0.0017, and 0.108 ng/day, respectively; the corresponding values for occupationally exposed individuals were 0.0001, 0.0175, and 1.08 ng/day. For the other 14 types of paper products (that is, papers other than thermal receipts and paper currencies), the EDI values for the general population and occupationally exposed individuals were the same. Among these paper types, the highest EDIs of BPS (calculated from fifth percentile, median, and 95th percentile concentrations in papers) were from the handling of airplane luggage tags (0.327, 0.559, and 0.800 ng/day), airplane boarding passes (0.223, 0.401, and 1.12 ng/day), and tickets (0.125, 0.766, 0.860 ng/day), followed by mailing envelopes (0.077, 0.126, and 0.989 ng/day). The median and 95th percentile values for total exposures ($\sum\text{EDI}$) from all 16 types of papers were 293 and 772 ng/day for the general population and 21806 and 57499

ng/day for occupationally exposed individuals, respectively. Among paper products, the major contributor to BPS exposure was thermal receipt papers, accounting for >88% of the total exposures (Table 2). Extremely high concentrations of BPS in thermal receipt papers explain its significance in contribution toward exposures (Table 1). The median and 95th percentile values for EDIs, based on a nominal body weight (bw) of 70 kg for adults, were 4.18 and 11.0 ng/kg bw/day for the general population and 312 and 821 ng/kg bw/day for occupationally exposed individuals, respectively.

It should be noted that several uncertainties exist in our exposure assessment of BPS via the handling of paper products. Due to the lack of data on transfer rates of BPS from paper to skin, we used a value reported for BPA. The daily intake value estimated in this study could be an underestimate of the actual exposure dose because the duration and frequency of exposure could be much higher than what we used as a nominal value in our EDI calculations. Further, we did not evaluate transfer of BPS from hand-to-mouth contact or inhalation exposure from ambient air during the handling of papers, which are likely important sources of exposure. Our study fills a knowledge gap by reporting the occurrence of BPS in various paper products. Analysis of BPS in foodstuffs, especially canned food products, is needed to assess the dietary exposure doses of this compound.

In summary, very high concentrations of BPS, ranging from a few tens of nanograms per gram to several milligrams per gram, were detected in thermal receipt samples collected from several cities in the USA, Japan, Korea, and Vietnam. A significant negative correlation existed between the concentrations of BPS and BPA in thermal receipt papers. This is consistent with the fact that BPA has gradually been substituted with BPS in thermal papers in some countries. BPS also was found (66%) in other paper types analyzed (such as magazines, mailing envelopes, food cartons, and napkins), at concentrations ranging from below <LOQ to 8.38 $\mu\text{g/g}$. Most of these papers were made from recycled paper, and the recycling of thermal receipt papers together with other papers is considered a source of BPS contamination. To our knowledge, this is the first study that describes the occurrence of BPS in a variety of paper products. The estimated daily intake of BPS (calculated from the median concentration) through dermal absorption from the handling of papers was 4.18 ng/kg bw/day for the general population and 312 ng/kg bw/day for occupationally exposed individuals. In view of the potential for occurrence and toxicity of BPS, further studies are needed to determine sources, pathways, and fate of this compound in the environment.

■ ASSOCIATED CONTENT

📄 Supporting Information

One table showing details of samples and concentrations of BPS in different regions of the paper currencies from various countries. Two figures showing a comparison of BPS concentrations in different portions of thermal receipt papers and BPS concentrations in paper currencies from various countries. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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