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Assessment of dioxin and dioxin-like compounds in mainstream smoke from selected US cigarette brands and reference cigarettes

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Abstract

Mainstream cigarette smoke (MSS) from 12 US cigarette brands and two reference cigarettes was evaluated to determine concentrations of dioxins (i.e., polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and dioxin-like polychlorinated biphenyls (PCBs)). The study included three 'tar' ranges based on Federal Trade Commission (FTC) determination: Low Yield (LY) $\leqslant$ 5.5, Medium Yield (MY) 9.6–12.2, and High Yield (HY) $\geqslant$ 14.5 mg/cig. Of the brands studied, the HY cigarettes yielded the greatest mean concentrations of 2005 World Health Organization Toxic Equivalents (WHO-TEQs) on a per cigarette basis. WHO-TEQ levels in LY cigarettes were significantly lower than for HY cigarettes ($p = 0.039$) on a yield per cigarette basis and WHO-TEQ concentrations correlated with 'tar' yield ($r = 0.73$, $p = 0.007$), as did concentration on a WHO-TEQ per body mass per day basis ($r = 0.73$, $p = 0.007$). However, a statistically significant relationship was not observed between 'tar' yield levels and WHO-TEQ concentrations on a per mg Total Particulate Matter (TPM) basis. Concentrations for all brands tested ranged from 0.44 to 3.88 fg WHO-TEQ/mg TPM. Maximum daily exposure estimates calculated from this range (0.004–0.074 pg WHO-TEQ/kg bw/day) are below the current WHO Tolerable Daily Intake range of 1–5 pg/kg bw/day.

Keywords: PCDD; PCDF; Mainstream smoke; PCB; Risk assessment; Cigarette

1. Introduction

Mainstream cigarette smoke (MSS) consists of over 4700 constituents that exist in a dynamic and chemically complex aerosol and can be categorized as existing primarily in either a gas phase or a gas suspended particulate phase (Dube and Green, 1982). The gas phase of a non-filter cigarette consists of nearly 500 individual volatile compounds, including carbon monoxide, nitrogen oxides, and ammonia and comprises roughly 95% of the weight of MSS (Hoffmann and Hoffmann, 1997). The particulate phase contains more than 3500 semivolatile and nonvolatile individual compounds, including nicotine, polynuclear aromatic hydrocarbons (PAHs) (Hoffmann and Hoffmann, 1997) and halogenated aromatic hydrocarbons (HAHs) (Muto and Takizawa, 1989; Ball et al., 1990; Löfroth and Zebhr, 1992; Smith et al., 2004). Composition of both gas and particulate phases vary with a broad range of cigarette design features (Borgerding and Klus, 2005).

MSS typically is analyzed for both yield and composition. Yield measurements include the determination of 'tar', nicotine, and carbon monoxide generated under standard conditions defined by domestic and international

Abbreviations: EMPC, estimated maximum possible concentration; FTC, federal trade commission; HAH, halogenated aromatic hydrocarbons; HY, high yield; ISO, International Organization for Standardization; LOD, limit of detection; LOQ, limit of quantitation; LY, low yield; MSS, mainstream cigarette smoke; MY, medium yield; PAHs, polynuclear aromatic hydrocarbons; PCB, polychlorinated biphenyl; PCDD, polychlorinated dibenzo-*p*-dioxin; PCDF, polychlorinated dibenzofuran; TCDD, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin; TEF, toxic equivalency factor; TEQ, toxic equivalent; TPM, total particulate matter; WHO-TEQ, World Health Organization toxic equivalent.

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regulatory bodies (i.e., US Federal Trade Commission (FTC), International Organization for Standardization (ISO)). MSS 'tar' is a chemically complex mixture defined as the Total Particulate Matter (TPM) in smoke less the weight of nicotine and water (Pillsbury et al., 1969). The 'tar' range in the worldwide marketplace is broad. The products studied in the present report represent that broad range through three 'tar' yield categories: Low Yield (LY), Medium Yield (MY), and High Yield (HY) delivering 1.0–5.5 mg, 9.6–12.2 mg, and 14.5–16.8 mg 'tar' per cigarette, respectively. A range of design features contribute to the 'tar' yield of a cigarette, including tobacco type, tobacco weight, filter composition, filter ventilation, structural dimensions, and papers (reviewed by Norman, 1999).

Methods to assess cigarette 'tar' yield have been standardized for regulatory and research and development purposes. These national and international protocols provide a standardized basis for comparing cigarette MSS yields. Under the FTC machine smoking regimen, applicable for determining cigarette yield ratings for comparison of products sold in the United States, a 35 ml puff of 2s duration is taken every 60 s (i.e., "35/60/2"). Fundamentally similar to the FTC method with regard to smoking regimen, ISO Method 4387 provides further guidance on cigarette conditioning parameters and product sampling procedures. A more intense smoking regimen used in the present study, 60/30/2, is designed to estimate smoke yields under more stringent smoking conditions. It should be noted that, while MSS yields as measured by an intense machine smoking regimen may estimate maximum potential smoke exposures, actual exposure to MSS constituents is highly variable and driven by a broad range of individual smoking behaviors.

Smoke composition investigations have focused on a range of applications, including regulatory, product development, and health risk assessment purposes. With regard to the latter, several compilations of chemicals present in cigarette smoke as potential toxicants have been published (Hoffmann and Hoffmann, 1997; Rodgman and Green, 2003). Qualitative and quantitative investigations of specific classes of toxicants, such as the PAHs, have also been published (Rodgman, 2001). Interestingly, the individual concentrations for many analytes bear a relatively strong positive correlation with MSS 'tar' yield (Chepiga et al., 2000; Borgerding and Klus, 2005).

Table 1
Features of the 12 cigarette brands studied

Cigarette Identification	Cigarette Description	FTC 'tar' (mg/cig) (35/60/2)	Length (mm)	Average TPM (mg/cig) (60/30/2)
76	LY	5.5	83	21.2
78	MY	10.3	83	31.8
79	HY	14.5	83	50.8
80	LY	5.0	83	18.5
81	LY	5.0	83	20.1
85	MY	10.5	83	37.9
86	MY	9.6	100	32.8
87	MY	12.2	120	40.1
88	HY	14.5	83	62.1
89	HY	16.8	100	56.9
91	HY	14.5	83	61.0
92	LY	1.0	100	6.7
K2R4F	MY	11.6	83.9	31.7
K1R5F	LY	2.0	83.9	8.9

LY: Low 'tar' Yield; MY: Medium 'tar' Yield; HY: High 'tar' Yield. LY, MY, and HY specify three 'tar' ranges based on the FTC machine smoking regimen. TPM: Total Particulate Matter.

The dioxins are members of a broader group of HAHs, which includes PCDDs, PCDFs, PCBs, and others. The term "dioxin" and "dioxin-like" includes the PCDDs, the 2,3,7,8-substituted PCDFs, and certain specific PCBs. These compounds are collectively called "dioxin" or "dioxin-like" because they induce a common pattern of toxic responses, exemplified by the family's prototypical and most potent congener, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD). Dioxins are highly lipophilic, ubiquitous contaminants of the global ecosystem and have been described in virtually every component of the biosphere, including air, aquatic sediment, fish, and wildlife and human adipose tissue, milk, and blood (Ballschmiter et al., 1980; DeVoogt and Brinkman, 1989; Brinkman and DeKok, 1989; Rappe et al., 1979; Schecter et al., 2006). Invariably, these compounds exist as complex mixtures of isomers and congeners in a diversity of analytes, complicating risk and hazard assessment efforts.

The dioxins induce a common spectrum of biochemical and toxic effects through a receptor-mediated mechanism of action, facilitating development and application of a relative potency factor risk assessment approach. Application of a Toxic Equivalents (TEQs) approach relies on several assumptions, with the most basic being that the combined effects of the different congeners are additive, although mixtures of PCDDs/PCDFs that also contain certain PCB congeners (e.g., PCBs 77 and 153) exhibit antagonistic interactive responses (Safe, 1992, 1998). In addition, it is assumed that all the individual compounds act through the same biologic or toxic mode of action and that dose-response curves for the different congeners are parallel (Safe, 1998). The TEQ approach is a scheme used to express the toxicity of an individual dioxin relative to that of TCDD. The overall potency or TEQ of a mixture is defined by the following equation:

$$\mathrm{TEQ} = \Sigma[C_i] \times \mathrm{TEF}_i$$

where C_i is the concentration of an individual congener and TEF_i is the Toxic Equivalence Factor (TEF) of an individual congener.

Individual TEF values have been revised by multiple organizations over the last decades; however, a 2005 World Health Organization (WHO) re-evaluation affirmed the plausibility and feasibility of the TEF approach for risk assessment of chemicals with dioxin-like properties (Van den Berg et al., 2006).