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Characterizing the Transport of Aluminum-, Silicon- and Titanium-Containing Particles and Nanoparticles in Mainstream Tobacco Smoke

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Abstract

The most commonly observed forms of aluminum, silicon and titanium in tobacco products are aluminum silicates (e.g., kaolin), silica and titanium(IV) oxide. These compounds are neither water soluble nor volatile at cigarette combustion temperatures. Rather, they are transported in mainstream tobacco smoke as particles after being freed by combustion from the tobacco filler and can induce pulmonary inflammation when inhaled. Aluminum silicate particles are the most frequently observed particles in the pulmonary macrophages of smokers and have become known as ‘smokers’ inclusions’. A relatively new technique, single particle triple quadrupole inductively coupled plasma-mass spectrometry was used to analyze aluminum-, silicon- and titanium-containing particle deliveries in cigarette and little cigar mainstream tobacco smoke, and to collect information on solid inorganic particles. The mass concentration of aluminum-containing particles transmitted in mainstream smoke was low (0.89–2.56 ng/cigarette), which was not surprising because aluminum silicates are not volatile. Although the collective masses (ng/cigarette) of aluminum, silicon- and titanium-containing particles under 100 nm diameter transported in mainstream smoke were low, an abundance of ‘ultrafine’ particles (particles<100 nm or nanoparticles) was observed. Limitations of the particle background equivalent diameter (the smallest detectable particle size (MassHunter 4.5 Software) due to the environmentally ubiquitous silicon background restricted the determination of silica nanoparticles, but silica particles slightly below 200 nm diameter were consistently detected. Aluminum- and titanium-containing nanoparticles were observed in all cigarette and little cigar samples, with titanium(IV) oxide particle deliveries consistently fewer in number and smaller in diameter than the other two types of particles. The highest concentrations of aluminum-containing particles (as kaolin) were in the nanoparticle range with much lower concentrations extending to the larger particle sizes (>100 nm). The number and range of particle sizes determined in mainstream smoke is consistent with pulmonary deposition of aluminum silicates described by other researchers as contributing to the ‘smokers’ inclusions’ observed in pulmonary macrophages.

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Introduction

Aluminum, silicon and titanium represent various inhalation health risks, and their roles in tobacco smoke are understudied. Though these compounds are ubiquitous in the environment, the most commonly studied exposures are from ingestion.

Sources of aluminum exposure are diverse, with the most common being municipal water sources where aluminum sulfate is added as a coagulant (1), antacids containing aluminum hydroxide, foodstuffs such as aluminum-containing baking powder and alum in some pickled vegetable products. Fortunately, less than 0.01% of ingested aluminum is absorbed in the digestive tract (2). Soluble aluminum compounds are neurotoxic to humans and toxic to plants (2–6). Silica naturally occurs as an insoluble solid or in colloidal form in soil and is present at low concentrations in water and various agricultural products (7). With a few exceptions, no significant health risks have been documented for ingestion exposure to silica (8).

Titanium(IV) oxide is not water soluble. Studies performed on rats, however, have shown that approximately 4.17% of 500 nm titanium(IV) oxide particles were taken up by the stomach and intestinal epithelium, and 0.02% accumulated in the blood and distributed to organs (9). Titanium(IV) oxide particles less than 100 nm diameter have been found to penetrate the blood–brain barrier and bioaccumulate (10), but little is known about the effects of chronic ingestion exposure.

Inhalation exposure to aluminum, silicon and titanium compounds in particle form may occur during combustion of tobacco (11, 12) or from the filter tip (13) as air and smoke are pulled through the cigarette or little cigar during inhalation. Although titanium(IV) oxide, silica and most aluminum compounds including aluminum silicates in tobacco and cigarette papers are not volatile, both volatile and non-volatile metal-containing substances including aluminum silicates and silicon-containing substances from tobacco are transported in the smoke aerosol (14–17). Once inhaled, larger fine particles (0.1 to 2.5 μm) may be ingested by bronchoalveolar or interstitial macrophages (18–20). Inhaled nanoparticles (ultrafine particles with one or more dimensions smaller than 100 nm) may be ingested by pulmonary macrophages along with the larger particles or may pass into the interstitial tissue (18–23). No matter their mode of entry into the lungs, pulmonary inflammation is the result of inhaling these solid particles (21, 22, 24), including nanoparticles (25). Inhalation of titanium oxide particles smaller than 100 nm has been shown to elicit greater inflammatory responses than those of larger fine particles in animal studies. This may be due to the greater surface area/mass ratio of the smaller particles, or perhaps is a consequence of the larger quantity of ultrafine particles than fine particles with the same total mass (22). If the particle inhalation exposure is chronic, respiratory disease may occur from chronic inflammation (24, 26).

Recent advances in analytical instrumentation and specialized methodologies are now available to investigate inhalation exposures from smoking. Quantitative analytical data on aluminum concentrations in tobacco can be obtained using modern instrumental capabilities, including medium resolution (R>4,000, 10% valley definition) with sector

field inductively coupled plasma-mass spectrometry (ICP-MS) together with clean sample preparation precautions (16). Before these developments, data on aluminum-, silicon- and titanium-containing particulate in mainstream tobacco smoke was scant due to analytical issues. Obtaining accurate measurements was complicated by the ubiquitous environmental presence of aluminum and silicon, potential for sample contamination, isobaric analytical interferences (e.g., $H^{12}C^{14}N^+$, $^{12}C^{15}N^+$, $^{13}C^{14}N^+$, $^{12}C^{16}O^+$, $^{14}N^{14}N^+$, $H^{13}C^{14}N$, $^{48}Ca^+$ and $^{32}SO^+$ in samples that contain sulfur) and the poor solubility of aluminum silicates, silica and titanium(IV) oxide in water and nitric acid.

While still challenging, investigations of these particles in mainstream tobacco smoke have become feasible because of recent hardware and software improvements enabling single particle analyses on ICP-MS instrumentation. In traditional ICP-MS, rapid elemental analysis of samples containing ultra-trace concentrations (ng/L) of dissolved metals is performed over long dwell times (0.1–1.0 s). In comparison, in single particle-ICP-MS (sp-ICP-MS), each intensity reading is analyzed over a shorter dwell time (0.1–3 ms) and plotted individually as a function of time (27). Thus, instead of a constant flow of metal ions through the ICP-MS, single particles enter the plasma and once ionized move through the mass analyzer as a cluster of ions. This cluster produces a spike in intensity above the dissolved background, and the counting and sizing of metal-containing nanoparticles is possible utilizing an important term in the sp-ICP-MS calculations, nebulization efficiency (i.e., transport efficiency (27, 28). Each pulse represents a single particle event dependent on short dwell times, constant flow rates and lower particle number concentrations. This correlates to frequency of the pulses being directly related to the number concentration of the particles (particles/L), and the intensity of the pulse is related to particle size (mass). Nebulization efficiency is the ratio of the amount of analyte reaching the plasma to the amount of analyte aspirated and must be accurate. The necessity for the nebulization efficiency value resides in the difference between the mass transport of a single nanoparticle through the nebulization system compared to dissolved ions in solution. Conversion of pulse intensity to particle mass using a dissolved metal calibration curve requires nebulization efficiency to relate concentration of the metal standard to a total mass flux (27, 28).

Previous studies on titanium(IV) oxide particle size detection limits or background equivalent diameters (BED) have reported minimum detectable diameters of 93 and 75 nm, respectively, using the ^{47}Ti and ^{49}Ti isotopes (29, 30). These less abundant isotopes were analyzed in simple aqueous matrices in evacuated (no gas) cell mode to avoid interferences from $^{48}Ca^+$ and $^{32}S^{16}O^+$ on the more abundant ^{48}Ti isotope. This study investigates the utility of single particle triple quadrupole inductively coupled plasma-mass spectrometry (sp-QQQ-ICP-MS), together with the solvent removal capability and increased sensitivity provided by a desolvating introduction system, to eliminate the interferences on $^{48}Ti^+$.

Aluminum silicates, silica and titanium(IV) oxide have not been included in smoking exposure-related cancer or non-cancer health risk calculations (31, 32) largely due to the lack of available analytical data. Silica is prevalent in mainstream smoke aerosol (15), and aluminum silicates are the principal intracellular inclusions in the pulmonary macrophages of smokers (18, 19, 33–36). Insoluble aluminum silicate particles are so prevalent in the bronchoalveolar and pulmonary interstitial macrophages of smokers that the particles

have been described as ‘smokers’ inclusions’ (18, 19, 33, 35). For these reasons, more information is needed on the characterization of solid particles in mainstream tobacco smoke.

This paper reports the results of investigation of prevalent immunotoxic aluminum-, silicon- and titanium-containing particle constituents in mainstream tobacco smoke from cigarettes and little cigars using sp-QQQ-ICP-MS. This information can be used to help evaluate the potential health consequences of such exposures.

Materials and Methods

Samples

Cigarettes and little cigars were purchased from online retail outlets of commercial establishments in the greater Atlanta, GA, USA, area between 2014 and 2016 and are trademarks of the respective manufacturers. Only authorized laboratory personnel had access to the samples.

Smoking conditions

Prior to smoking, cigarettes and little cigars were conditioned according to ISO Standard 3402 (1999, 37). Smoking parameters were established using an RM20H rotary smoking machine (Borgwaldt KC, North Chesterfield, VA, USA) using filter ventilation blocking cigarette holders as per World Health Organization (WHO) smoking conditions (WHO TobLabNet Official Method SOP 01, formerly Health Canada Method T-115) (38). Air flow, leak and puff volume tests were performed daily. Adjustments were made as necessary to ensure compliance with smoking protocols. The smoke aerosol [total particulate matter (TPM), ISO Standard 4387, 2000 (39)] was collected using electrostatic precipitation (24 kV) in high-purity fused silica quartz tubes.

Nanoparticle standard and characterized compound preparation and analysis

Aluminum oxide, aluminum silicate (kaolin) and titanium(IV) oxide nanoparticle standards and characterized materials (approximately 0.01 g) were weighed and added to ultrapure water in acid-cleaned polypropylene tubes in an ice bath. These materials were sonicated for 15 minutes at 100% amplitude with a Qsonica Q125 probe sonicator (Newtown, CT, USA) in pulse mode (8 seconds on and 2 seconds off) with a 3-mm titanium horn probe. Sonicated nanoparticles were serially diluted with ultrapure water until the final dilution in 1% (v/v) *N,N*-dimethylformamide (DMF) in H_2O solution (~10 ng/L concentrations) for matrix-matched analysis.

Smoke sample, blank and standard preparation and analysis

TPM from 10 cigarettes was dissolved in 30.0 mL DMF (Trace-Select for inorganic trace analysis, Sigma, St. Louis, MO, USA). Aliquots of the TPM solutions (500 μL) were diluted to 50.0 mL with 18 MΩ·cm ultrapure water in polymethylpentene class A volumetric flasks (1% (v/v) final DMF concentration).

Nanoparticle concentrations (particles/L) and mass concentrations (ng/L) were calculated using MassHunter version 4.5 nanoparticle software (Agilent—Tokyo, Japan). Response factors (cps/ppb) for calculation of nanoparticle mass and size were determined by dilution of aluminum, silicon and titanium standards (High Purity Standards, Charleston, SC, USA) to 1000, 5000 and 1000 ng/L, respectively, in 1% (v/v) DMF/H_2O matrices after background subtraction of the same matrix. The mass fraction for aluminum in aluminum oxide (Al_2O_3—Alfa Aesar—NanoArc™ 40–50 nm size) reference nanoparticles used for method validation was 0.529 (particle density: 3.97 g/cm^3, Figure 4). The mass fraction for aluminum in TPM was 0.209. This value corresponded to the mass fraction of aluminum as kaolin ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$—particle density: 2.59 g/cm^3, TPM—Figure 1, Aldrich Nanopowder—Figure 5), based on our observations of kaolin aluminum silicates as the predominant form of aluminum in tobacco and mainstream smoke (15, 17) and on the large quantities of kaolin observed in the pulmonary macrophages of smokers (18, 19, 33, 35). The silicon mass fraction for particle calculations in diluted TPM samples was 0.467, which corresponds to the silicon mass fraction in silica (SiO_2—particle density: 2.59 g/cm^3, Figure 2). The titanium mass fraction for particle size determination in diluted NIST SRM 1898 (Information Values for Size) and TPM samples was 0.599, the titanium mass fraction in titanium(IV) oxide (TiO_2—particle density: 4.23 g/cm^3, Figure 3).

ICP-QQQ-MS instrumental parameters for smoke analysis

Samples, standards, blanks and quality controls were introduced by means of a peristaltic pump through 0.64 mm i.d. peristaltic pump tubing at 0.22 rps via an Elemental Scientific Apex perfluoroalkoxy (PFA) desolvating introduction system (ESI, Omaha, NE, USA), a C400E PFA nebulizer (Savillex, Eden Prairie, MN, USA) and PFA transfer tube into an Agilent 8900 (Tokyo, Japan) ICP-QQQ-MS. Liquid flow rate into the Apex system was determined by establishing the time required for uptake of 10.0 mL of the diluted TPM solution. Carrier gas was optimized for all modes of analysis at 1.02 L/min with analyte-specific optimum sampling depths at 1500 watts RF power. Q1 entrance voltages were optimized at −50.0 V for suppression of polyatomic ions for all analytes. Octopole cell parameters were optimized at −18.0 V octopole bias and energy discrimination at 0.0 V to eliminate polyatomic interferences on ^{27}Al and ^{28}Si, and −18.0 V octopole bias and energy discrimination at −8.0 V for ^{48}Ti. Axial acceleration was optimized at 1.0 V in all gas modes with 7.0 mL/min H_2 cell gas (Si), 5.0 mL/min H_2 cell gas (Al) and 5.0 mL/min H_2 cell gas with 25% O_2 (Ti). Acquisition dwell time was 100 μs with 30 s acquisition times after 30 s stabilization times for all analytes. Nebulization efficiency was determined using NIST standard reference material 8012 ‘30 nm’ gold (Au) nanoparticle standard diluted to 0.48 ng/L Au in a 1% v/v DMF/ultrapure water matrix; the same matrix that was used for diluted TPM samples. Two methods were utilized for calculating nebulization efficiency: particle size calibration (calculation of nebulization efficiency by measuring size-characterized gold nanoparticles along with dissolved standards) and particle concentration calibration (using a known gold standard particle number concentration) (27).

Dissolved concentration method limits of detection

The method limit of detection (LOD) was determined both by calculating the standard deviation of 65 analytical run procedural blanks multiplied by three followed by conversion

of units from μg/L to μg/cigarette and by plotting standard deviations of procedural blanks and standard spikes in procedural blanks versus concentrations according to Taylor (40).

Results and Discussion

The two particle calibration methods (size and concentration) provided similar nebulization efficiencies. Although desolvation apparently decreased the differences, particle number concentrations resulting from particle size calibration are frequently inaccurate without an appropriate internal standard (41). Current software for single particle-ICP-MS, however, lacks capabilities for internal standard correction. Issues that could affect signal intensity drift, such as gradual carbon buildup on the cones and lens assembly, were rectified by recalibration and recalculation of the nebulization efficiency for each subsequent sample analyzed and confirmed by a repeat analysis of the dissolved calibration standard for each analyte for quality control purposes (42).

Particle nebulization efficiency averaged 31% (N=137), as a result of using a desolvating introduction system with the ICP-QQQ-MS. This introduction system enhanced nebulization efficiency and provided an approximately 4-fold increase in analyte signal intensity compared with a standard double-pass spray chamber, while decreasing polyatomic interferences that result from solvent elements such as carbon, nitrogen and oxygen interacting with analytes from the solvents. Use of this introduction system together with the ICP-QQQ-MS resulted in lower BEDs and smaller particles detected and quantified. Comparisons to analysis with other sample introduction systems and ICP-MS instrumentation combinations resulted in smaller-sized nanoparticles detected and quantified rather than these particles being quantified along with the dissolved fraction by the software. Removal of interferences on the more abundant ^{48}Ti isotope using sp-QQQ-ICP-MS, together with the solvent removal capability and increased sensitivity provided by a desolvating introduction system, lowered the BED for TiO_2 particles in this study to less than 7 nm in a matrix of mainstream tobacco smoke tar dissolved in DMF and diluted 1:100 in water..

The analytical benefits were also illustrated by improved BEDs for aluminum silicate particles that averaged between 20 and 30 nm (Table I, Figure 1). Aluminum (as kaolin aluminum silicate) mean particle sizes in mainstream smoke from cigarettes and little cigars ranged from 67 to 96 nm (median sizes 60 to 78 nm, Table I).

Titanium(IV) oxide mean particle sizes in mainstream smoke ranged from 29 to 38 nm (median sizes 20 to 25 nm, Table I) and were in the nanoparticle range.

Unfortunately, the smallest mean silica particle size that could be quantified in mainstream smoke using sp-QQQ-ICP-MS was slightly less than 190 nm BED because of the ubiquitous environmental silicon background (43) in ultrapure water and other high purity solvents. Silica mean particle sizes ranged from 258 to 331 nm (median sizes 225 to 309 nm, Table I), which were at the lower end of the fine particle size range. Clusters of smaller silica particles obtained from mainstream cigarette smoke have been observed using scanning electron microscopy with energy-dispersive X-ray spectroscopy (15). BEDs for silica in

mainstream smoke ranged from 108 to 147 nm (Table I, Figure 2). Since there were negligible aluminum containing particles greater than 125 nm diameter relative to silicon containing particles in the larger size range, it was possible to assign the larger silicon only particle fraction (no aluminum in that size range) as silica rather than as aluminum silicates. It was not possible to determine whether the silica fractions were crystalline or amorphous using sp-QQQ-ICP-MS. Silica may occur externally on tobacco leaves as quartz from soil or internally as amorphous phytolithic silica (17). Silica and silicates were described as accounting for 52% of 'mineral particulate matter' in lungs of 85 autopsy subjects, 77% of whom were smokers or ex-smokers (44).

The mean numbers of particles transported in mainstream smoke aerosol ranged from 4.8×10^5 to 2.7×10^6 silica particles per cigarette, 3.4×10^5 to 2.5×10^6 aluminum silicate particles per cigarette and from 3.2×10^5 to 2.3×10^6 titanium(IV) oxide particles per cigarette. These results are in agreement with the identification of phytolithic silica, soil silica and aluminum silicates, which were observed to be principal particles within or on the surfaces of unsmoked tobacco leaves (17), in mainstream smoke tar (15) and with the large numbers of aluminum silicate particles reported in pulmonary macrophages of smokers (18, 19, 33–36). Titanium(IV) oxide is common in soils (45) and therefore likely to deposit on tobacco leaves as do soil silica and aluminum silicates.

Analyses of dissolved species were more sensitive than they might have been with a less efficient instrument combination due to the observed low background threshold. The method LODs for dissolved species were 45 ng Si per cigarette, 2.0 ng Al per cigarette and 1.0 ng Ti per cigarette. The dissolved masses of Si, Al and Ti transported in mainstream smoke from every cigarette and little cigar brand were lower than the respective method LODs without exception. These results were as would be expected for the extremely insoluble forms of these elements as silica, aluminum silicates (15) and titanium(IV) oxide, and further confirm that the principal forms of these elements in mainstream smoke were insoluble particles rather than dissolved species.

The numbers of aluminum silicate, silica and titanium(IV) oxide particles transported in mainstream smoke are considerable and are consistent with the aluminum silicates described as 'smokers' inclusions' in pulmonary macrophages (18). The 'platelike' aluminum silicate structures described by Brody and Craighead (1975) were also observed as long-lived particles by Agius *et al.* (46), who reported that approximately 3 years cessation of smoking was required before the inclusions were no longer observed in alveolar macrophages. Girod and King (2005) described chronic obstructive pulmonary disease as a dust-induced condition, with aluminum silicate from tobacco smoke commonly being the dust. A study of rats subchronically exposed to crystalline quartz and amorphous silicas showed that while crystalline silica (predominantly on tobacco leaf surfaces) caused by far the greatest pulmonary fibrotic collagenization; the lung collagen content also had increased in response to exposure to all amorphous silicas, such as the phytolithic silica produced within the leaves. This implies that although the sp-QQQ-ICP-MS results could not distinguish between crystalline and amorphous silica, inhaling silica is detrimental to pulmonary health regardless of the type of exposure. Aluminum silicates, silica and titanium(IV) oxide particles all contribute to pulmonary inflammation when inhaled. Oberdörster *et al.* (22)

described the selective deposition of sub-100 nm particles in the alveoli, and Ferin and Oberdörster (21) showed that ultrafine particles that deposit in the alveoli during inhalation were translocated to the interstitial tissue in greater quantities than larger particles and that the increased translocation was accompanied by an acute inflammatory response even after exposure to 'nuisance' particles such as titanium(IV) oxide.

These results contribute to the growing body of evidence that health-relevant amounts of fine inorganic particles and ultrafine nanoparticles that, when inhaled, may contribute to chronic pulmonary inflammation and, ultimately, fibrotic damage to the lungs.

Conclusion

A novel approach was developed for measuring aluminum silicate, silica and titanium(IV) oxide nanoparticles in mainstream smoke particulate. Utilization of a desolvating sample introduction system together with sp-QQQ-ICP-MS provided lower BEDs and high analyte sensitivities for ultra-trace quantitative analysis of samples and particle size distributions. The data obtained confirm that significant exposure to fine and ultrafine insoluble inorganic particles could occur as a consequence of smoking cigarettes and little cigars. These elements were mainly present in insoluble particulate forms. As new analytical tools become available for inorganic particle characterization, they will allow further investigations into the deliveries of inorganic particles in mainstream smoke to address this gap in understanding the health risks from smoking. Also needed are improvements in instrumentation and software that would allow the use of internal standards and multi-point calibrations. Such improvements would permit lower BEDs and greater accuracy and precision in determination of particle number concentrations.

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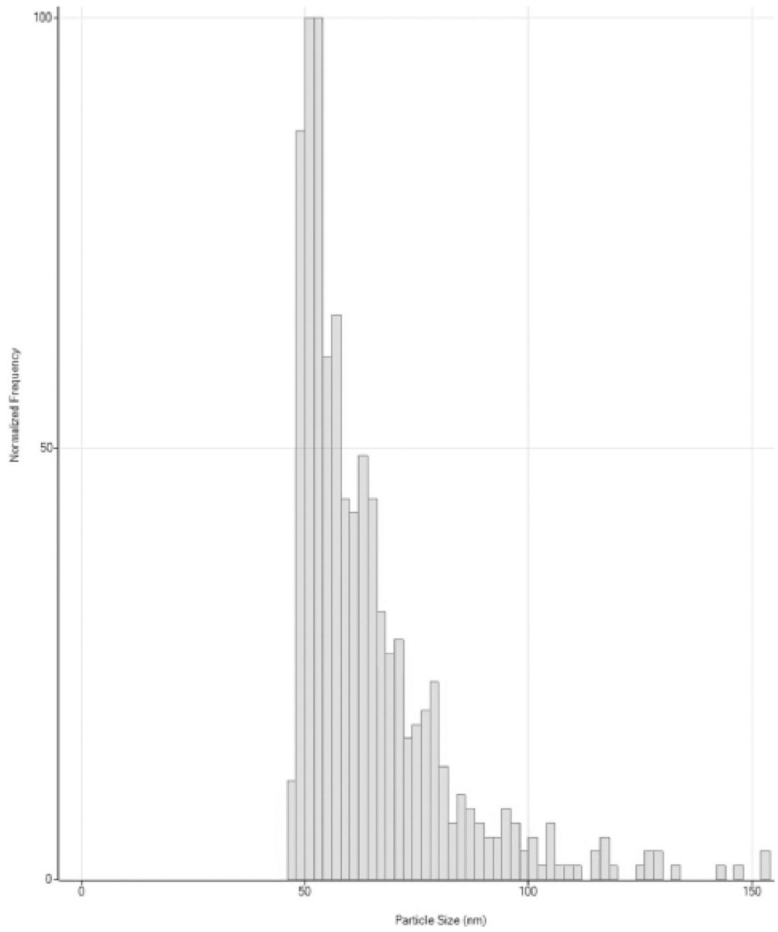

Figure 1.

Aluminum-containing particle size distribution as kaolin (Al_2 Si_2 $O_5(OH)_4$) obtained from diluted American Spirit Orange TPM solution (BED: 27 nm, mean size: 65 nm, most frequent size: 54 nm).

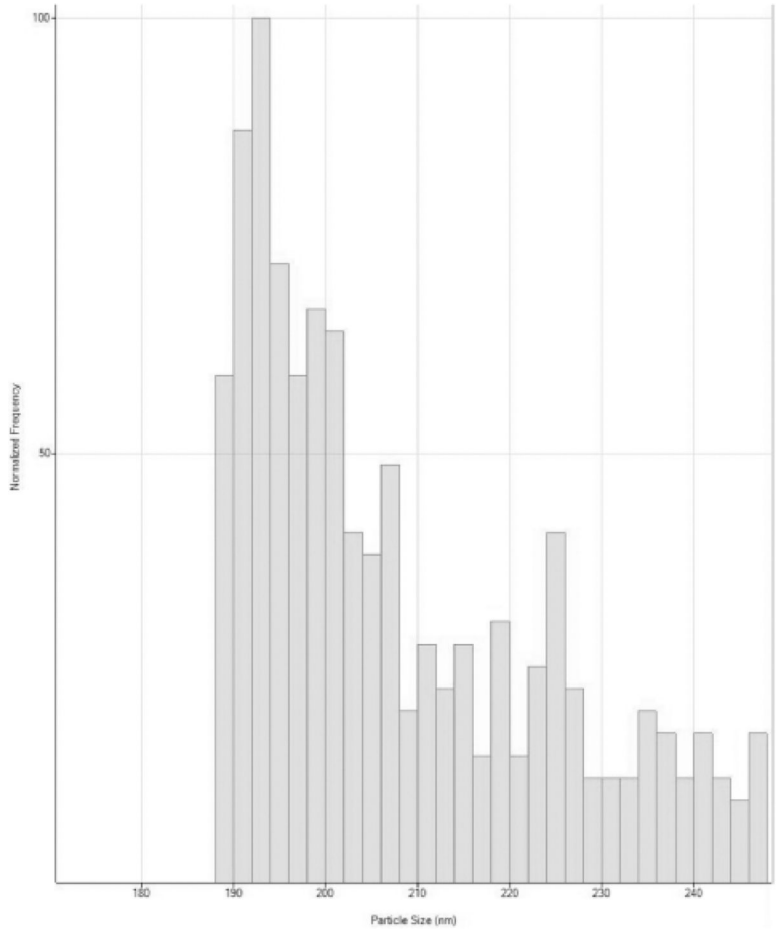

Figure 2.

Silica particle size distribution obtained from diluted American Spirit Orange TPM solution (BED: 133 nm, mean size: 244 nm, most frequent size: 194 nm).

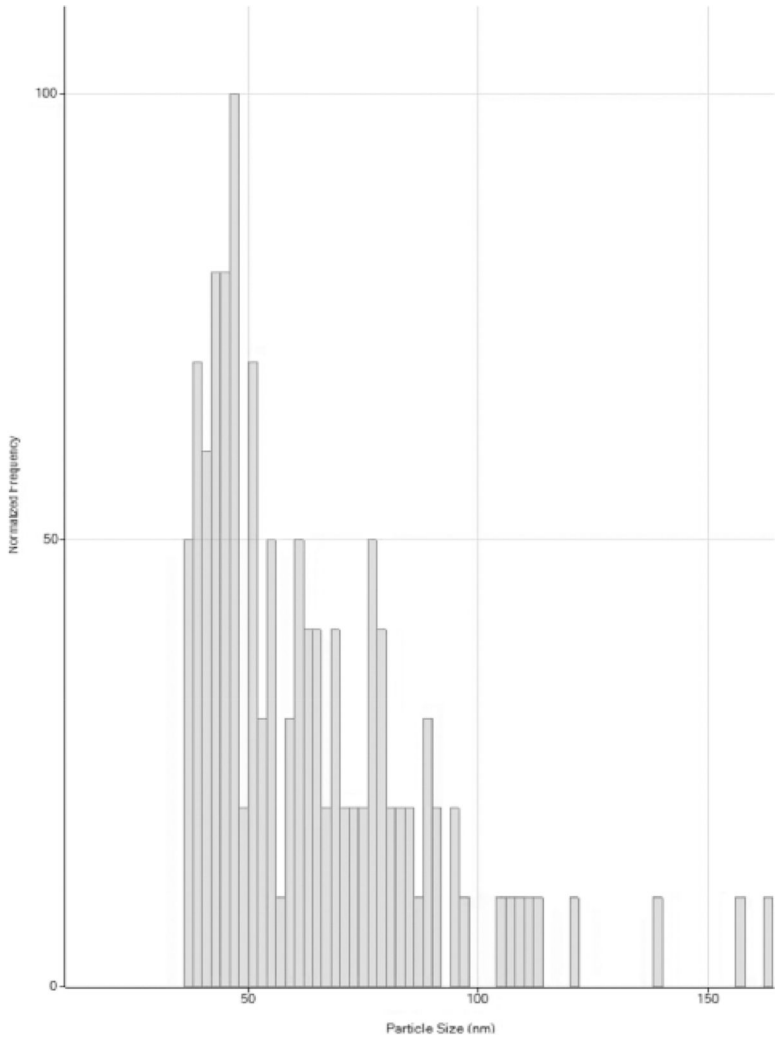

Figure 3.

NIST SRM 1898 TiO_2 NPs (10 ppt) in 1% DMF/H_2O matrix—BED: 5.69 nm, mean size: 64 nm.

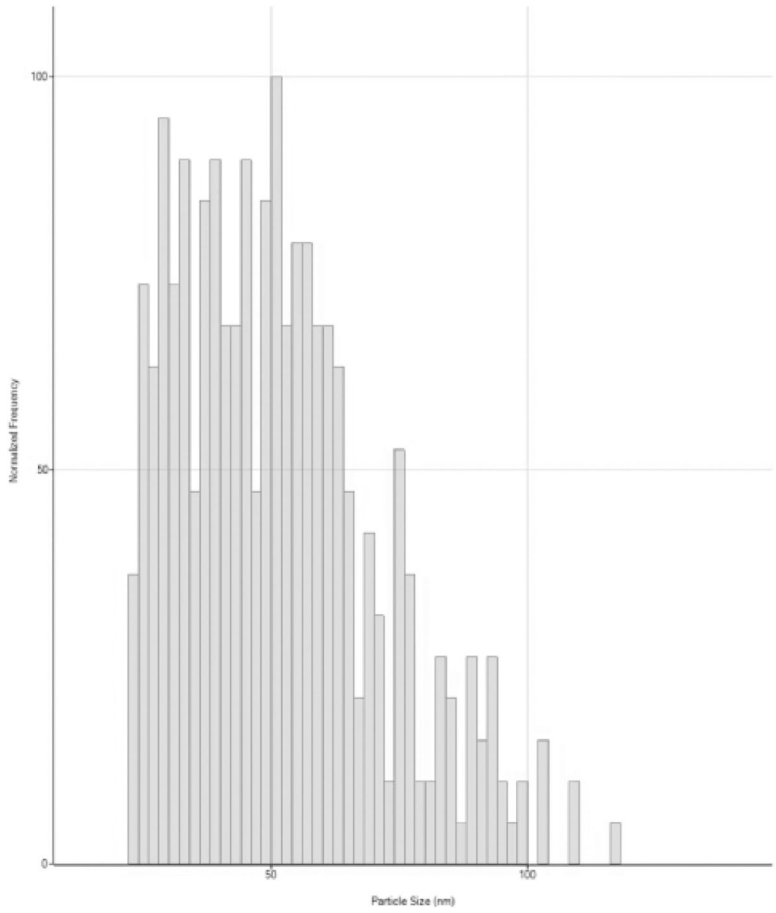

Figure 4.

Al_2O_3 NPs (10 ppt) in 1% DMF/H_2O matrix—BED: 9.25 nm, mean size: 52 nm.

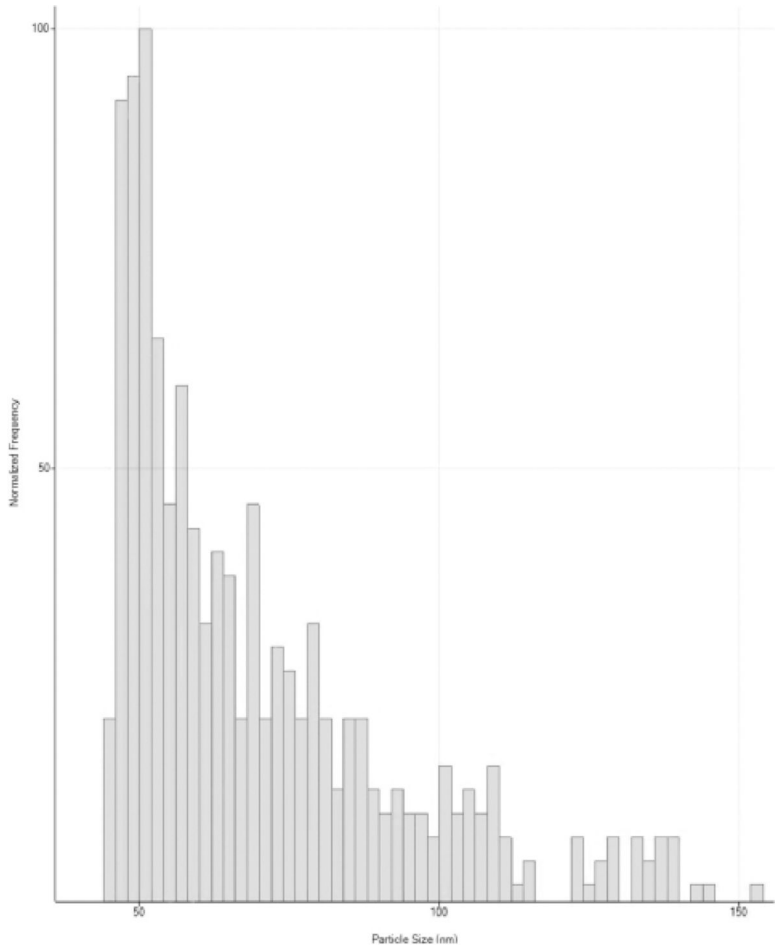

Figure 5.

Aluminum-containing particle size distribution as kaolin (Al_2 $Si_2O_5(OH)_4$) NPs (13 ppt) in 1% DMF/H_2O matrix—BED: 20.40 nm, mean size: 72 nm.

Table I.

Concentrations, Sizes, and Background Equivalent Diameters in Mainstream Cigarette and Little Cigar Smoke with Standard Deviations

$N = 14^a$	Particles transported per cigarette	Particle mass transported (ng per cigarette)	Background equivalent diameter (BED; nm)	Median size (nm)	Mean size (nm)
Swisher Sweets					
SiO_2	$4.8 \pm 3.0 \times 10^5$	29.7 ± 28.7	108 ± 16	264 ± 34	294 ± 50
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$9.3 \pm 5.8 \times 10^5$	2.13 ± 2.36	22 ± 6	68 ± 13	82 ± 16
TiO_2	$3.9 \pm 4.3 \times 10^5$	0.18 ± 0.34	7 ± 1	25 ± 4	33 ± 11
3R4F					
SiO_2	$5.2 \pm 2.1 \times 10^5$	39.5 ± 23.6	112 ± 15	271 ± 39	310 ± 44
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$3.4 \pm 2.0 \times 10^5$	0.89 ± 0.64	30 ± 7	78 ± 14	96 ± 16
TiO_2	$5.0 \pm 9.5 \times 10^5$	0.38 ± 0.39	8 ± 1	25 ± 2	38 ± 14
Merit Gold					
SiO_2	$2.7 \pm 3.1 \times 10^6$	59.3 ± 53.9	147 ± 16	306 ± 61	325 ± 61
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$2.5 \pm 3.8 \times 10^6$	1.01 ± 0.88	22 ± 4	60 ± 14	67 ± 15
TiO_2	$3.7 \pm 4.6 \times 10^5$	0.17 ± 0.27	6 ± 1	20 ± 3	29 ± 14
Pall Mall 100s					
SiO_2	$7.4 \pm 9.5 \times 10^5$	47.6 ± 63.4	140 ± 42	292 ± 98	317±105
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$9.2 \pm 8.7 \times 10^5$	1.10 ± 0.96	27 ± 5	70 ± 11	82 ± 16
TiO_2	$3.2 \pm 3.2 \times 10^5$	0.23 ± 0.23	7 ± 7	23 ± 23	33 ± 34
Marlboro Black 100s					
SiO_2	$1.1 \pm 1.3 \times 10^6$	55.2 ± 51.1	142 ± 17	309 ± 54	331 ± 58
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$1.6 \pm 1.9 \times 10^6$	1.36 ± 0.72	24 ± 3	66 ± 12	79 ± 16
TiO_2	$8.3 \pm 8.6 \times 10^5$	0.21 ± 0.18	6 ± 2	23 ± 3	30 ± 6
American Spirit Turquoise					
SiO_2	$2.4 \pm 3.0 \times 10^6$	116±115	144 ± 30	295 ± 55	319 ± 53
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$1.3 \pm 1.2 \times 10^6$	1.81 ± 0.91	28 ± 3	71 ± 16	84 ± 19
TiO_2	$4.6 \pm 6.0 \times 10^5$	0.48 ± 0.49	7 ± 1	25 ± 5	42 ± 10
American Spirit Orange					
SiO_2	$1.3 \pm 1.2 \times 10^6$	59.0 ± 33.6	112 ± 14	225 ± 35	258 ± 40

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***N* = 14**[a]	**Particles transported per cigarette**	**Particle mass transported (ng per cigarette)**	**Background equivalent diameter (BED; nm)**	**Median size (nm)**	**Mean size (nm)**
$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	$2.0 \pm 2.0 \times 10^6$	2.56 ± 2.00	29 ± 7	76 ± 16	86 ± 17
TiO_2	$2.3 \pm 3.1 \times 10^6$	0.49 ± 0.41	7 ± 2	27 ± 4	34 ± 8

[a] *N*=14 is the number of replicate analyses of each cigarette or little cigar—10 cigarettes or little cigars smoked per analysis.