Risk Ranking Framework to Assess the Health Hazard of Nanomaterial Containing Products in an Industrial and Consumer Application Setting

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ABSTRACT

The unique combination of size, structure, morphology, and physical/chemical characteristics of nanomaterials presents challenges to understanding the potential hazards and health risks of engineered nanomaterials. A hierarchical risk ranking framework was developed for two nanomaterials, carbon black and carbon nanotubes, as a case study for industrial and consumer use settings. A numerical risk ranking scheme was derived from product and nanomaterial characteristics, use and exposure patterns, and toxicological information. Primary drivers of risk ranking estimates included releasability from the matrix or system, exposure pathway and intensity, bioavailability, biopersistence and severity of health effects. Evident differences in hazard ranking were observed between nanostructured materials of similar elemental composition but different morphologies. This framework offers a novel strategy to identify and prioritize the hazard and potential health risks of nanomaterials and associated products throughout their lifecycle.

Keywords: health hazard, carbon nanotube, carbon black, consumer product, industrial

1 INTRODUCTION

A hierarchical risk ranking framework was developed as a methodological approach to identify and prioritize hazards and health risks of nanomaterials in both consumer and manufacturing settings. Nanomaterials are used in paints and surface coatings to improve product performance, including water repellence, scratch resistance, durability and antibacterial properties. Both carbon black (CB) and carbon nanotubes (CNTs) are used in a variety of manufacturing settings and are also utilized in some coatings for consumer product applications. CB and CNTs were considered ideal preliminary material candidates to evaluate the feasibility of the hierarchical risk ranking framework, because 1) similar industrial and consumer product scenarios could be identified for these nanostructured materials, and 2) these materials represented drastically different physicochemistries despite their similar elemental composition.

2 METHODS

A numerical risk ranking framework was developed based on a customized hierarchical scheme of product and nanomaterial characteristics, use and exposure patterns, and toxicological information. The basic framework combined several conceptual schema (Figure 1): 1) Classification according to location of nanoscale structure in the system (Hansen and Gunter, 2007; Hansen et al., 2008); 2) Control banding for selection of exposure control methods (Paik et al., 2008; Zalk and Paik, 2009); 3) Hazard ranking and alternatives assessment for chemicals of concern (US EPA, 2011).

Scoring of individual risk ranking factors within the hierarchical framework was derived from a variety of sources, including: classification of industry, process, and activity patterns (Crump, 2000; ECHA, 2008; Health Canada, 2011; Koponen et al., 2011; Koponen et al., 2009; Paik et al., 2008; Patel, 2011; SCENIHR, 2009; Wijnhoven et al., 2009; Zalk and Paik, 2009), thresholds of toxicokinetic information (ECHA, 2008), and ranking of severity of human health effects (US EPA, 2011).

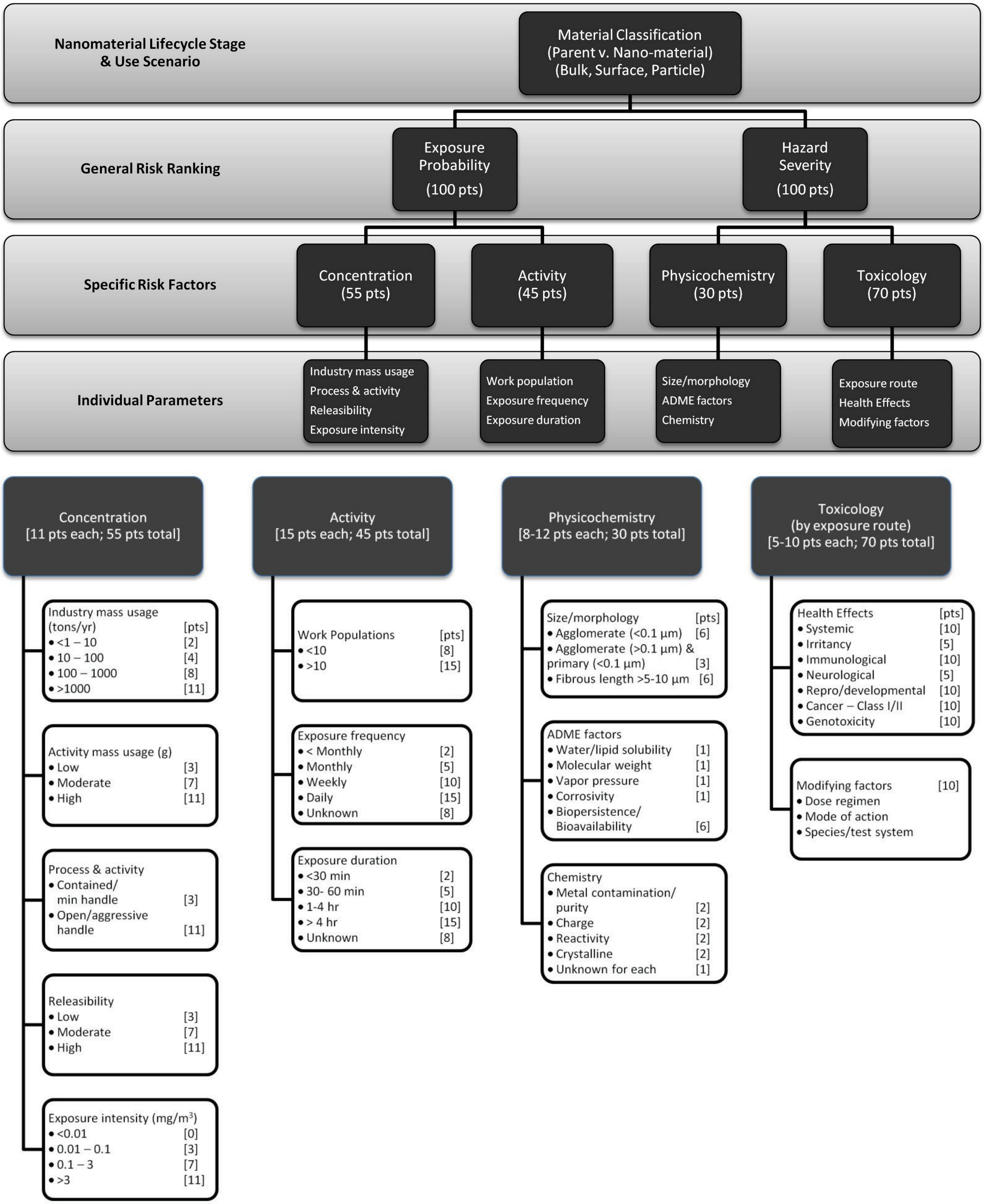
A numerical risk ranking scheme was derived from product and nanomaterial characteristics, use and exposure patterns, and toxicological information for an industrial setting whereby parent or raw nanostructured materials (i.e., CB, CNTs) are utilized for manufacturing and for a consumer product setting whereby paints and surface coatings containing CB or CNTs are manipulated (e.g., sanded).

3 RESULTS

A comparison of the risk ranking scores derived for CB and CNT in the proposed framework showed that the ranking scores were primarily driven by hazard severity. Differences in scoring were evident for physicochemical characteristics including morphology, biopersistence, and surface reactivity, whereas agglomeration and solubility were similarly scored between the two nanomaterials. Distinguishing toxicological characteristics and uncertainties or lack of research data in certain parameters for CNTs led to a conservative hazard severity ranking score for CNT compared to CB.

A relatively low hazard severity score for CB (<40 combined points) is supported by a large experimental research database, well understood mode of action, and epidemiological information on human health effects. In addition, negative reproductive/developmental effects and lack of systemic, mutagenic and inflammatory effects at low or non-particle-overload dosing conditions further supported a relatively low hazard severity score for CB. While the toxicological research dataset for CB span several decades, there continue to be areas of uncertainty which are reflected in some of the individual toxicology/health effects scores.

Figure 1. Hierarchical Hazard and Risk Ranking Framework for Nanomaterials and Nano-Enabled Products



For example, CB is classified as a Group 2B carcinogen (*possibly carcinogenic to humans*) based on animal data, however evidence in humans is inadequate. The human relevance of tumor effects observed in experimental animal studies have been questioned because data points to species specific effects in animals, which are secondary to inflammation in "particle overload" conditions. Additionally, although CB show negative results for mutagenicity, several *in vitro* and *in vivo* animal studies have indicated that CB can induce cytogenetic effects. However, it is noteworthy that these effects are likely related to particle overload conditions which cause secondary effects on DNA due to inflammation and oxidative stress. Some uncertainties in the relevance of particle overload in rat lungs compared with human lung toxicology remain.

CNT research has been accumulating, but there are certain areas that necessitate further investigation. Unique physicochemical characteristics and preliminary suggestion of systemic, inflammatory, reproductive/developmental and genotoxic effects support a relatively high hazard severity score (>70 combined points). The carcinogenic effects of CNTs have not been elucidated, however recent data indicate that the material is associated with genotoxicity, inflammation and oxidative stress suggesting carcinogenic potential. Results in animal studies have indicated that CNTs can produce pulmonary fibrosis, granulomatous inflammation, and possible central nervous system effects. Although these biological pathways are relevant in humans, specific responses to CNTs remain unclear. Lack of detailed information on CNT mode of action, human data, as well as relevant exposure studies, also significantly influenced risk ranking.

Comparison of the different nanomaterials in the risk ranking framework showed the highest ranking values for the scenario of handling bulk CNTs in a manufacturing setting and lowest ranking values for sanding paints and coatings containing CB in a consumer use scenario. Exposure probability scores were driven largely by mass usage and exposure intensity potential for both consumer and industrial settings.

Not surprisingly, airborne concentrations in a consumer setting of sanding paints and composites were far lower than that observed handling raw bulk materials. For example, a consumer setting for sanding of paints and composites containing CB showed an airborne concentration of 0.0015 mg/m^3 for total suspended particulate, whereas composites containing CNTs were associated with a concentration of 0.007 mg/m^3 based on total elemental carbon (Health Canada, 2011; Methner et al., 2012). In contrast, a manufacturing setting for handling bulk CB have been reported to range from 0.17 to 4.04 mg/m^3 (respirable dust) and CNTs range from 0.0078 to 0.3208 mg/m^3 (total suspended particulate) (Gardiner et al., 1992; Lee et al., 2010; Muller et al., 2005).

Due to a lack of data on the prevalence of nanomaterials in paints and coatings, mass usage was estimated by multiplying annual production by the fraction of material used for paintings and coatings. Annual CB production is about 1.6 million tons and of that about 10% is dedicated to non-rubber uses in paints, plastics, paper, etc. (Crump, 2000). Annual CNT production is about 10,000 tons and of that about 69% is dedicated to composites and plastics (Patel, 2011). These surrogate estimates of content and prevalence of use of CB or CNT-containing coatings would be greatly improved by industry and market reporting of the concentration of nanostructured materials contained within these products, as well as the extent of the product market share.

4 DISCUSSION

Although additional health-based research would reduce uncertainties to identify materials of greatest potential risk, this approach provides a basic structure to classify and prioritize potential risks of existing and newly developed nanomaterials or nano-enabled products. Utilizing CB and CNTs in the manufacturing and consumer setting as a case-study, this risk ranking framework showed that settings involving CNTs ranked highest compared to CB with the following relative ranking: CNT manufacturing > CNT aggressive consumer use (e.g., sanding paints/coatings) > CB manufacturing > CB aggressive consumer use setting (e.g., sanding paints/coatings). Differences in risk ranking were primarily associated with specific physicochemical and toxicological parameters. Minimal differences in exposure probability existed between the two materials for each exposure scenario. However, differences in exposure probability were evident when comparing nanomaterials in a manufacturing versus consumer setting. Several factors were identified to appreciably influence potential exposure and release of nanomaterials contained within composites, resins and coatings, including the matrix type, nanomaterial dispersion or chemical bonding within the matrix, exposure frequency/duration, and mechanism of product manipulation.

To better understand potential exposures and health risks associated with nanomaterials used in composites, coatings and resins in various applications, future studies would benefit from standardized analytical methods to characterize release and physicochemical properties of nanomaterials within and released from the matrix. In addition, risk scoring in our analysis was heavily influenced by the extent and strength of the toxicological database. Further research on the influence of different physical and chemical properties (e.g., size, structure, morphology, surface chemistry) of nanomaterials released from composites, coatings and resins in relation to their relevance to properties and toxicology of pure bulk nanomaterials would greatly improve our ability to apply the most relevant toxicology information for hazard assessments and comprehensive health risk assessments.

This framework offers a novel streamlined approach to identify and prioritize nanomaterial hazard and potential health risk taking into account information about the parent product and substructure, use and exposure propensity, and aspects of physicochemisty that influence toxicity criteria throughout the nanomaterial lifecycle. This risk ranking framework should be helpful in prioritizing the needs for future comprehensive risk assessments, toxicity testing, and exposure control efforts for engineered nanomaterials used in a variety of occupational, consumer and environmental settings.

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