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Overview of Risk Management for Engineered Nanomaterials

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Abstract

Occupational exposure to engineered nanomaterials (ENMs) is considered a new and challenging occurrence. Preliminary information from laboratory studies indicates that workers exposed to some kinds of ENMs could be at risk of adverse health effects. To protect the nanomaterial workforce, a precautionary risk management approach is warranted and given the newness of ENMs and emergence of nanotechnology, a naturalistic view of risk management is useful. Employers have the primary responsibility for providing a safe and healthy workplace. This is achieved by identifying and managing risks which include recognition of hazards, assessing exposures, characterizing actual risk, and implementing measures to control those risks. Following traditional risk management models for nanomaterials is challenging because of uncertainties about the nature of hazards, issues in exposure assessment, questions about appropriate control methods, and lack of occupational exposure limits (OELs) or nano-specific regulations. In the absence of OELs specific for nanomaterials, a precautionary approach has been recommended in many countries. The precautionary approach entails minimizing exposures by using engineering controls and personal protective equipment (PPE). Generally, risk management utilizes the hierarchy of controls. Ideally, risk management for nanomaterials should be part of an enterprise-wide risk management program or system and this should include both risk control and a medical surveillance program that assesses the frequency of adverse effects among groups of workers exposed to nanomaterials. In some cases, the medical surveillance could include medical screening of individual workers to detect early signs of work-related illnesses. All medical surveillance should be used to assess the effectiveness of risk management; however, medical surveillance should be considered as a second line of defense to ensure that implemented risk management practices are effective.

1. Introduction

The products of nanotechnology are relatively new, generally coming into commerce the last 10–15 years [1]. To date, there are more than 1,600 nanotechnology-enabled products in commerce [1–3]. Each nanomaterial and the products that contain them are developed and produced by workers. Workers are the first people in society to be exposed to new technologies and materials such as those arising from nanotechnology. Moreover, if there is

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to be vast societal benefit from nanotechnology, society needs to be assured that it is being developed responsibly. Attention to the safety and health of workers is the foundation of responsible development that ultimately delivers benefit to society while protecting human health and engendering public trust [4,5].

Risk management (RM) is arguably the most critical step in the protection of workers. Driven by hazard, exposure, and risk information, risk management involves evaluating the extent of risks, and deciding on the most appropriate exposure control measures. The role of RM in nanotechnology may be best considered by taking what can be termed a “naturalistic” view where RM is treated as an evolving set of guidance and control concepts and part of a larger system because it is early in the development of the technology. Employers and workers want RM guidance because there are still vast uncertainties about hazards, exposures, and risks. Because of these uncertainties, hazards, exposures, and risk management approaches should be seen as parts of a dynamic system—one that will be changing, and one where RM approaches and guidance will need to be continuously evaluated, improved, and verified as risk information becomes more substantial.

A naturalistic view of RM for ENMs is illustrated in Figure 1. RM is part of a dynamic iterative system that involves societal and workplace level efforts. At the societal level, two overarching principles prevail. First, is that workers have a right to a safe and healthy workplace and a right to know about potential hazards. Second, employers have the responsibility to provide a safe and healthy workplace and keep the workers safe (workers have the responsibility to cooperate with employers in this regard).

The critical issues to date are “what are the risks” and “what is safe”. Responsible development of nanotechnology, in the face of uncertainty of the potential health risks (see [6–9] for review of the evidence), requires that a precautionary approach to risk management should be taken [4].

2. Societal level risk management

At the societal level, the initiators of risk management are laws, standards, regulations, guidance—soft and hard laws. These efforts need to be seen globally, as well as locally, since what happens in one country may affect what happens in another, and as Murashov et al. (2012) [10] noted: “Anticipatory international consensus standards established at the introductory stage of nanotechnology could also potentially hinder the “race to the bottom” where nations compete for jobs by lowering workplace safety standards.” In addition to general control guidance, the critical feature of societal level risk management is the development of OELs. Two approaches to developing OELs have been identified, one where there is adequate health information to conduct a quantitative risk assessment to derive an OEL, and the other, where there is limited information requiring a pragmatic approach that relies on professional judgment (Figure 2).

Examples of the first approach include the NIOSH recommended exposure limits (RELs) for titanium dioxide [11] and carbon nanotubes (CNT)/carbon nanofibers (CNF) [12]. Examples of the second approach include British Standards Institute (BSI) guidance [16], the provisional German/Dutch Nano Reference Values (NRV) [17] and is described by

Kuempel et al [18]. Variations in non-regulatory OELs based on risk assessments have been conducted including those for carbon nanotubes, with proposed OELs ranging from 1–50 $\mu g/m^3$ [12–15,19]. These values may seem quite divergent but, in fact, this divergence generally reflects variability in the use of safety/uncertainty factors and the manner which the working life risk of exposure is assessed (up to 45 years). Moreover, there is greater divergence between proposed OELs for nanomaterials and the OELs for the same bulk material. This discrepancy is evident in the U.S. when comparing the proposed OELs for CNTs with the OEL for graphites. These bulk OELs are often hundreds of times higher than for their nanoscale variants. Where pragmatic OELs are developed, hazards and control bands may be used to identify what level of control to apply. The critical research need for hazard and control banding is to further improve the parameters that define the risk bands (i.e. determining the health risk). The banding strategies developed for nanomaterials have been recently reviewed [20], and approaches to link quantitative risk assessment with exposure control banding schemes (for categorical decision-making and validation) have been described [21].

3. Workplace risk management

The actual application of RM for ENM occurs in the workplace. There is a range of workplaces in which workers are potentially exposed to ENMs that include research laboratories, start-up and pilot operations, manufacturing, incorporating manufactured ENMs in products, and end of life activities including recycling (Figure 3).

Also, exposure scenarios include maintenance activities in each of these types of workplaces, and transport between them. These various workplaces could require different risk management strategies.

The principal approach that is recommended for risk management of ENMs is the establishment of ENM-risk management program that is integrated into the overall company health and safety program or system (Figure 4) [22]. The core of the ENM risk management program, as with all occupational safety and health (OSH) risk management programs, is implementation of the well-established hierarchy of controls (Figure 4).

Experience for more than 100 years has shown the effectiveness of the hierarchy of controls (e.g. engineering and personal protective equipment [PPE]), to control fibers and dusts in general industry, biologically active powders in the pharmaceutical industry, and radioactive aerosols in the nuclear industry [22–25]. One limitation in employing an effective RM process is that workers and various employers downstream from the original manufacturer may not know whether materials they receive are nanomaterials or contain nanoparticles due to insufficient or inadequate information on safety data sheets (SDS). Recent studies have shown a large percentage of ENM SDS's were in need of improvement [26,27].

4. Effectiveness of risk management

The limited data that are available on exposure supports the need to periodically evaluate the application and effectiveness of the controls used to manage ENM risks. It is useful to consider the risk management process holistically as a cascade of interventions to prevent harm to workers (Figure 5). Each step represents opportunities to intervene to prevent adverse effects. Interventions at the higher levels can reduce the burden downstream. Working from a cascade framework brings together disparate elements into a cohesive system that is "greater than the sum of its parts [28]." An important element in the cascade is surveillance which provides feedback to upstream processes. The environmental monitoring, part of such surveillance, presents unique challenges since currently available analytical methods and instrumentation may not provide the specificity or sensitivity to cover the broad range of nanomaterials being produced or used. However, a combination of exposure assessment options may provide adequate data to appropriately support risk management needs [29–31].

Ultimately, the effectiveness of risk management is based on the extent to which employers have adopted precautionary guidance to control exposures in the face of scientific uncertainty about the extent of the health risk. Numerous government agencies and other organizations have issued precautionary guidance for nanomaterials (e.g., [16,32–34]). Initial surveys of industries conducted in 2004 and 2010 on the use of effective risk management practices have shown that the implementation of precautionary guidance is not at the highest levels [35]. These surveys had relatively low response rates and could have been influenced by responder bias (i.e., more response by the more adherent employers). There is need for further national and global assessment of the adoption of precautionary guidance, and the development of targeted information campaigns for sectors and subsectors where adoption is low.

5. Future issues in RM for ENMs

5.1. Need to develop categorical OELS

It is unlikely that it will be possible to assess toxicologically (using animal studies) all the ENMs in, or entering, commerce [21,36,37]. Therefore, it may be necessary to screen materials individually or as categories and assign them to hazard and control categories (based on physical-chemical parameters). This screening could involve simple characterization of materials and matching them on structure-activity relationships (SAR), or other analogous factors where the hazard is known. For some materials, where high commercial volumes are anticipated, screening may also include a tiered approach that includes a literature assessment followed by *in vitro* testing and *in vivo* testing for those most likely to be of concern.

5.2. Designing out hazards

Hazards of ENMs can be mitigated by considering the hazard potential in the initial design phase of the ENM and in the design of production processes. A recent workshop in 2012 assembled material scientists, toxicologists, and occupational safety and health specialists to address these issues [37]. Such prevention through design (PtD) or "safety by design" efforts need to be supported by corporate leadership that is committed to protecting the workforce and the environment by adopting sustainable practices throughout the life cycle and value chain of an ENM. The challenge is to design a material that maintains the desired functionality while mitigating the potential toxicity. Similarly, production processes can be designed to reduce exposures and hence risk.

5.3. Monitoring the health of the workforce

Thus far, the health of the ENM workforce has been considered in an anticipatory way by conducting animal studies, extrapolating results to workers, and implementing precautionary controls. The nanomaterial workforce also should be continuously monitored and assessed. Funding agencies and employers' associations should commit resources to support significant workforce health surveillance and assessment. This will involve support for medical surveillance as well as for exposure registries, and epidemiological studies [38,39]. Monitoring of the workforce is critical to demonstrating that nanotechnology is being developed responsibly. A pioneering effort in this regard is the national surveillance program in France which initially will monitor workers exposed to carbon nanotubes and titanium dioxide [40]. Similar efforts are needed in other countries. There are sufficient preliminary findings in animals and from experience with incidental nanoparticles to suggest health endpoints to look for (e.g. various respiratory and cardiovascular effects) [6,8,9,41,42]. Animal studies have also yielded an informative array of candidate biomarkers of exposure and effect that could be assessed cross-sectionally and possibly prospectively [43]. There are many technical and logistical issues in developing and conducting epidemiologic studies of workers exposed to ENMs, but there should be a commitment of funds for international research to pursue the health of the current and future workforce [44–45].

5.4. Address advanced nanomaterials

The current generation of "passive" nanomaterials are predicted to be succeeded by generations of more advanced materials [10, 46]. These materials will be advanced in comparison to the current generation by being more active, more integrated and complex, and capable of being linked in systems. It is not known if these materials will be more hazardous than the current generation, but in some cases, they will be designed to be more interactive with biological systems, to change properties during functional operation in response to a stimulus or external signal, and be assembled from the "bottom up" from atoms or molecules [10]. For the most part, these materials appear to be still in laboratory development and not in commerce. But there is not a clear understanding of their ultimate use, location, and the current workforce handling them. More significantly, it is not known to what extent such materials are being targeted for toxicological tests, screening, or anticipatory hazard assessments. There is need to address all of these uncertainties before, like with the passive nanomaterials, they are introduced in commerce without any indications of their potential health risks.

6. Conclusions

The potential health risks of exposure from nanomaterials to workers need to be anticipated and managed if nanotechnology is to be developed responsibly. Absent such efforts, workers may be harmed and society deprived of the timely realization of benefits of the technology. Critical for effective management of risks of nanomaterials is the need for a naturalistic view—one that sees where science and society are in the development of the technology. Nanotechnology is new, early in its natural history, and it needs to be treated cautiously. By actively managing the risks to the workforce through the hierarchy of controls, and then confirming the effectiveness of those management efforts through medical screening, surveillance and epidemiologic studies, society can demonstrate a responsible approach to the development of nanotechnology.

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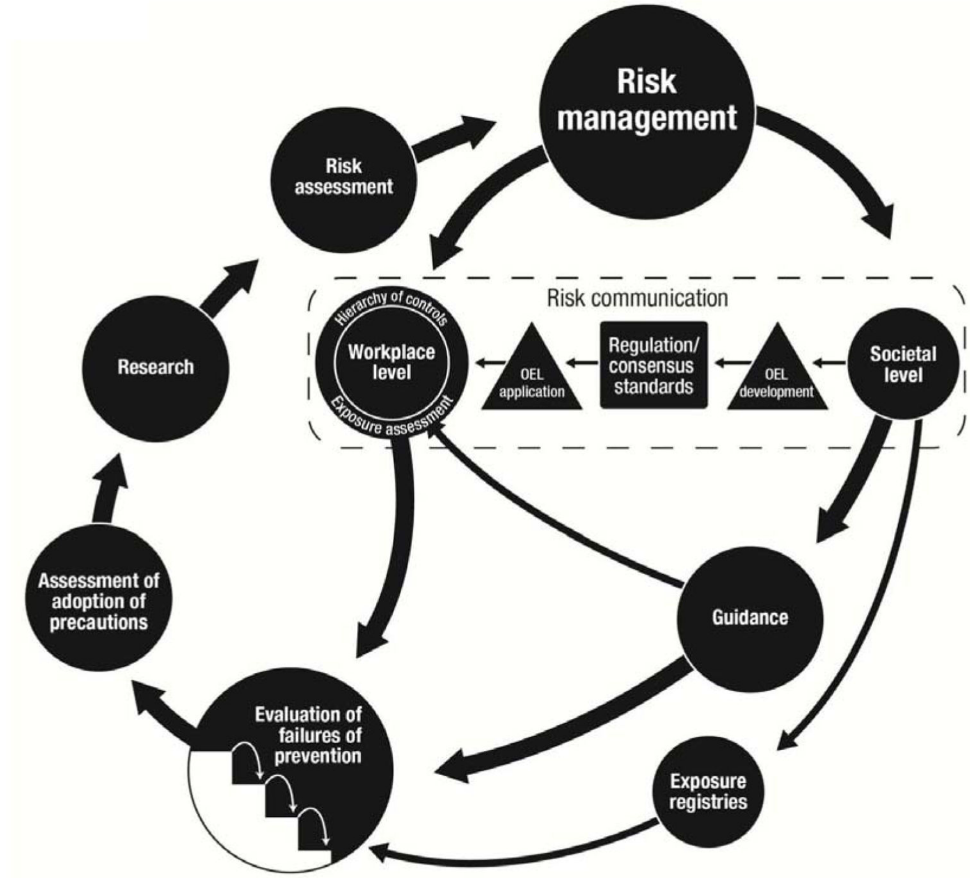

Figure 1.

Naturalistic view of occupational safety and health risk maintenance for nanomaterials.

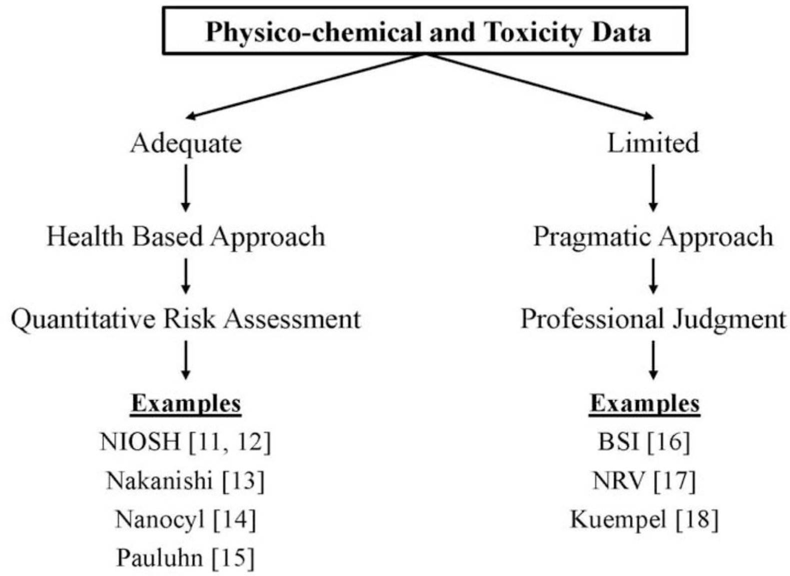

Figure 2.
Approaches to developing Occupational Exposure Limits for engineered nanomaterials.

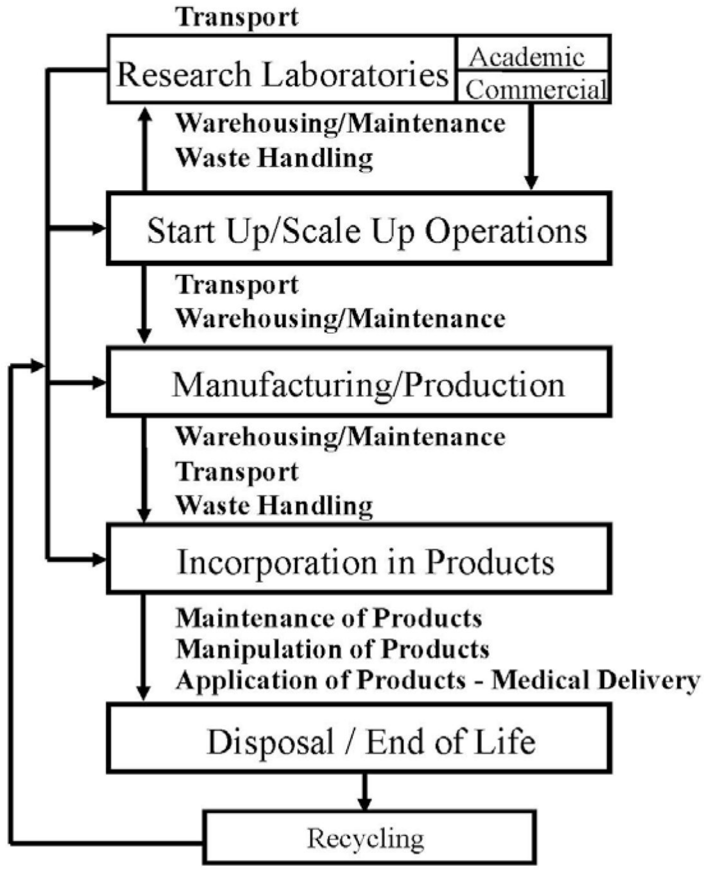

Figure 3.
Workplaces where exposures to ENMs could occur (Adapted from [22]).

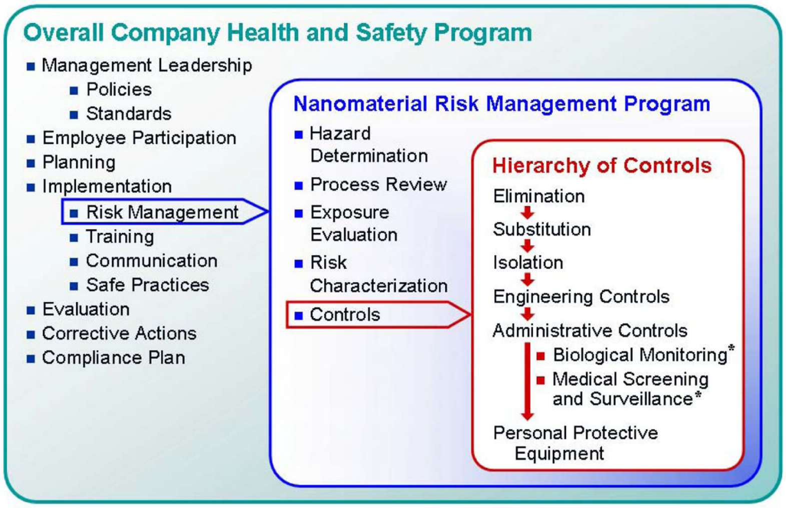

Figure 4.

Nanomaterial risk management should be part of an overall company health and safety program [22]. The elements with an asterisk are not actually part of the classical hierarchy of controls, rather they help evaluate controls; however, they may be viewed as part of a hierarchy of prevention that include control and evaluative strategies. (Reprinted with permission of the journal.)

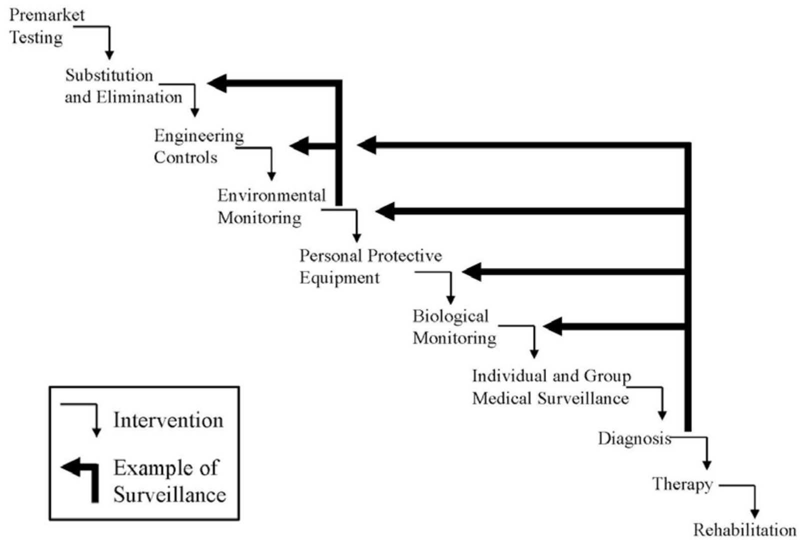

Figure 5.

The cascade of occupational health is a model that illustrates the interacting roles of interventions and surveillance in risk management. (Adapted from [28]).