Defining Intake Fraction

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Introduction

Activities such as comparative risk analysis, life-cycle assessment, emissions trading and sustainable development are creating a growing demand for reliable and consistent information about the potential adverse effects of the thousands of chemicals released to the environment. This demand has fostered measurement and modeling efforts that link emissions to the resulting human exposures and subsequent health

effects for a wide range of human products and activities, such manufacture and disposal of consumer goods, cooking, smoking, energy conversion, industrial production, and agriculture.

For many pollutants, a preliminary estimate of the human health risk that is posed by an environmental release can be determined from the combination of three factors: (1) the quantity released; (2) the incremental intake per unit release; and (3) the risk of adverse effect per unit intake. This paper addresses the second term, the emissions-to-intake relationship. As discussed in a recent literature review [1], several researchers have independently developed similar approaches for relating source emissions to human intake for various pollutants and exposure pathways. Consequently, multiple terms, definitions, and units exist for what appears to be a single, yet multifaceted concept. [2-10,11]. But there are inconsistencies both in terminology and definitions among various researchers quantifying emissions-to-intake relationships. Differences in definitions leads to unnecessary complexity in comparing results from different research groups. Inconsistency in terminology when the same quantity is being calculated leads to further lack of transparency.

Coordination and cooperation among these groups and communication of results is better served by the use of consistent terms, definitions, and units. Even without an organized effort to unify the language, a consistent set of terms might ultimately emerge. But this process could take considerable time, particularly if there is little initial agreement, as is the case for intake fraction.

To facilitate this transition we formed a working group[#] and prepared this article to communicate our recommendations. We strove to derive a set of terms and associated definitions that are descriptive, simple, accurate, and consistent both with common usage and usage in all relevant disciplines; are flexible to permit application over a broad range of potential uses; and reflect consensus among a large number of researchers. We propose the term *intake fraction* (*iF*) as the primary label for quantifying the emissions-to-intake relationship.

Because the effort to employ intake fraction is in its early stages and is gaining momentum, now is the time to build consensus on terminology. Doing so will allow us to communicate more effectively both among ourselves and also with practitioners in related fields.

Evolution of the Concept

In the environmental literature, researchers have proposed various terms to express source-to-intake relationships. These terms and the associated metrics have been applied to a wide range of issues. The first known articulation of the source-to-intake relationship was in the field of radiation protection. The term *committed dose* was introduced to reflect the fraction of a release of radioactive elements that entered a defined population through multiple exposure pathways [12]. Some who worked on radiation dosimetry proposed that this approach could be extended to other materials.

[#] The working group has been designated as the Intake Fraction Working Group (IFWG). The current members of the IFWG include D.H. Bennett, J.S. Evans and J. Levy, Harvard University; D. Hattis, Clark University; E.G. Hertwich, Norwegian University of Sci.&Tech.; O. Jolliet, M.D. Margni, and D. Pennington, EPFL; T.E. McKone, W.W. Nazaroff, and K.R. Smith, University of California, Berkeley; and W.J. Riley, Lawrence Berkeley National Laboratory.

For crustal elements, Cohen [13] calculated the probability that an element released to soil, surface water, oceans, or air would move into human populations. B. Bennett extended this concept along a series of exposure compartments or reservoirs (air, water, food, humans) by systematically assessing multipathway source-to-intake relationships, using the term *exposure commitment* [2].

Over last two decades, the literature has also provided many examples of calculations relating the inhaled intake of a substance to the amount emitted to air. This represents an important step beyond the concentration-source ratio (χ / Q) introduced in the early 1970's by Gifford and Hanna [14] for interpreting the significance of atmospheric dispersion. More recently, there have been several efforts to estimate multimedia intake by a population or an individual relative to specified release (to air, water, or soil). In most of these assessments the multimedia source-to-intake relationship can easily be converted to an intake fraction. A brief summary of the development of these ideas is provided in Table 1, while a more comprehensive and detailed history is provided by Evans et al[1]. Although the broad concept is the same, there are significant differences among terms and units in many of the studies.

Proposed Terms and Definitions

We propose the term *intake fraction*, designated *iF*, to quantify emissions-to-intake relationships. The intake fraction is defined as the integrated incremental intake of a pollutant, summed over all exposed individuals, and occurring over a given exposure time, released from a specified source or source class, per unit of pollutant emitted. The definition is expressed in the equation below:

$$iF = \frac{\sum_{people,time} \text{intake of pollutant by an individual (mass)}}{\text{mass released into the environment (mass)}}$$

There are two dimensions over which the pollutant intake is summed, population and time. In actuality, when a pollutant is released into the environment there is a distribution of individual exposures within the exposed population. We can quantify the exposure to an individual and define this as the *individual intake fraction*, designated iF_i. Thus, the intake fraction can be represented as the individual intake fractions summed over all members of the potentially exposed population.

Intake fraction can be calculated over different time horizons, depending on the purpose to which it is to be put, for example the policy question. Depending on the horizon chosen, the exposed population can thus include not only current, but in some cases, future generations. It may seem attractive to specify an infinite time horizon as the default value. This causes no problem for those compounds that decay rapidly in the environment because a short-term intake fraction will essentially be equal to the infinite intake fraction. For extremely long-lasting pollutants, however, such as metals, in order to calculate infinite intake fraction the fate of the pollutant in the environment as well as potential human exposure must be predicted hundreds or thousands of years in the future, adding much uncertainty to the calculation. In such cases, one may choose to use a shorter time horizon, acknowledging potential differences in the result. This issue has been faced in other fields; for example, global warming potential is usually determined for several time horizons, leaving the choice of which to use to the analyst depending on the particular needs of each assessment [15].

The intake fraction assumes a linear relationship between emissions and population intake. Where nonlinearities occur, e.g. because of environmental chemistry or physiological processes, an incremental intake fraction can be defined as the first derivative of the relationship between emissions and intake evaluated at current conditions.

The criteria we considered in determining the terms are discussed below, building on the foundation established by Zartarian et al. [16] for defining exposure and related concepts.

Consistency with common usage. Most previous expressions of the emissions-to-intake concept used either "exposure" or "dose" to characterize the contact and / or uptake of a pollutant by a human population. Although there is variation in the way these terms are defined across the many disciplines involved in environmental health, most accept that "exposure" represents "the *contact* between an agent and a target [16]." In contrast, "dose" is "the amount of pollutant that is absorbed by a target [16]." In addition, the term "dose" is not consistently defined among different health scientists. Rather than recommending either of these terms, we propose "intake" because it refers to "the amount of pollutant that enters a target after crossing a contact boundary[16]." The contact boundaries for inhalation, ingestion, and dermal exposure are defined, respectively, as passage through the nose (or mouth for oral breathing), mouth, and skin.

Dimensional independence. Structuring the intake fraction as a dimensionless parameter offers the advantage of numerical constancy, independent of the system of units used for intake or emission. This represents an enormous advantage for clear

communication over the endless possibility of dimensional metrics. For transient release scenarios, the intake fraction is made dimensionless by dividing the time-integrated intake by the total quantity released. For steady-state release and exposure conditions, intake fraction can be obtained as the rate of intake to the rate of release, both expressed in the same units of mass per time. In both cases, to obtain *iF*, one must literally measure or calculate the *fraction* of a released substance that eventually enters the receptor population, hence the use of the term "fraction" in the proposed terminology.

Parsimony. For an idea to take root and be widely used, it should be expressed concisely. The term *intake fraction* is frugal.

Uniqueness. Some of the previously proposed terms have other definitions as well, which can cause confusion. We are not aware of any other definitions for intake fraction.

Breadth of application. By being independent of species, environmental media, and exposure pathways, the *iF* concept offers broad potential applicability. The definition is valid not only for inhaled substances from air emissions, but also applicable to all exposure pathways through all environmental compartments and release media. By basing the measure on intake, the analyst is able to incorporate information on any or all exposure routes. The concept is not limited to a single method of evaluation. For example, intake fraction can be estimated by means of simple "back of the envelope methods" or by sophisticated modeling tools that simulate environmental fate and transport as well as human activities. It can also be determined by experimental methods. For example, a pollutant tracer can be released at a constant

rate and the steady-state concentration of the tracer measured in an exposure medium such as air, water, or food. The intake fraction for the tracer would be the concentration times the rate of intake of the medium divided by the rate of release.

Attributes of the Intake Fraction

To facilitate further understanding of the intake fraction, we focus on three key attributes--(i) the extrinsic, as opposed to intrinsic, nature of the measure, (ii) compatibility with dose-response functions, and (iii) ability to be disaggregated into its components.

It is important to stress that the intake fraction depends on several factors, including chemical properties of the contaminant, emission locations, environmental conditions (climate, meteorology, land use, etc.), exposure pathways, receptor locations and activities, and population characteristics. Hence, the intake fraction is not an *intrinsic* but an *extrinsic* property of a pollutant. For example, if one were to release a volatile pollutant into a crowded auditorium, a greater fraction would be inhaled than if the same pollutant were released into the same auditorium when empty or outdoors in a sparsely populated region. As a result, the emission scenario and the exposure conditions are essential attributes that must be communicated in an *iF* calculation. This idea is illustrated in Figure 1, where we make example *iF* calculations for two benzene exposure scenarios. These calculations show a significant *iF* difference for the same compound with the two exposure scenarios yielding intake fractions four orders of magnitude apart. The large difference of intake fraction in these scenarios demonstrates the ability of the *iF* to make clear distinctions between scenarios.

One cannot forget that the intrinsic properties of a chemical can lead to differences in the intake fraction for the same release scenario. For example, if two volatile chemicals are released into the same urban air shed, the one with a shorter environmental lifetime would have a lower intake fraction. The differences in intake fraction have been found to be even more extreme in cases where there is significant partitioning of the pollutant into the food chain. For example, based on measurements from a recent US EPA, the *iF* of TCDD was on the order of 0.002 for the US in 1995 [17,18]. This is up to five orders of magnitude greater than calculated *iF* values for a volatile compound with a short atmospheric half-life, demonstrating the clear distinction between compounds [17].

When the effects of cumulative pollutant intake can be represented by a linear dose-response function, the intake fraction can easily be combined with the dose-response information to yield an overall measure of risk. When health effects depend on exposure rather than dose, the intake fraction must be modified to quantify the toxic effect. For example, if the toxic effect is based on the average exposure concentration, this concentration must be calculated from the intake fraction by backing out the breathing rate and number of exposed individuals. In cases where the toxic response is dependent on the rate of intake, rather than the average or cumulative intake, or if there is a threshold in the dose response function, the intake fraction must be disaggregated spatially and temporally in order to make risk estimates. But it is important to recognize that for most *iF* calculations, the place (and time) where pollutants are released are likely to be as important as their relative toxicities in determining health impact. Indeed, *iF* may be even more useful than toxicity for many important pollutant

categories, such as small particles, where health impacts per unit intake do not vary nearly as much as *iF*.

Although in some cases only the aggregate intake fraction of an entire exposed population will be of interest, there are other situations in which it becomes important to disaggregate the intake fraction into its component parts along one or more dimensions. The notation for specifying such disaggregation is specified in Figure 2. Four potential examples are disaggregation across individuals, time periods, exposure routes and exposure pathways, each briefly discussed below.

As specified in the relationship between individual and population parameters, the intake fraction is the sum of the individual intake fractions over all exposed individuals, potentially including future generations. However, from a practical standpoint, we are unlikely to be able to quantify the exposure to each individual. A clear statement of the population under study should be included and a comment should be made on the anticipated relationship between the population studied and the actual population. In a typical assessment, we can construct *iF* from the summation of average individual intakes within population subgroups, summed across all potentially exposed subgroups. For some applications, it may be sufficient to use an average intake for the entire population, while in other cases one may need to quantify the intake for numerous subsets of a population in order to capture variability in exposure. This could occur in cases where steep gradients in both the concentration and population density occur coincidentally around a release location.

One might also choose to disaggregate among routes of intake (i.e. inhalation, ingestion, or dermal intake). Such differentiation may yield an understanding of the

underlying fate and transport of the pollutant or be important for identifying control options. Additionally, if the pollutant reaches different target organs, is absorbed at a different rate, or metabolized differently when inhaled, ingested, or taken in through the skin, it is important to quantify the potential impact via each intake route. In this case the toxicity would vary between routes of exposure and the health risk would be proportional to an appropriately weighted sum of the disaggregated intake fractions, as opposed to a simple sum. One of the challenges in determining the intake through the ingestion route is that one must consider both regional food production rates and regional food consumption sources since pollutant may partition into the locally produced food but be consumed by an individual living outside the region of impact as defined by the natural transport of the pollutant.

In some cases, it may be of interest to quantify source-to-intake relationships from different exposure pathways for various exposed populations. An exposure pathway describes more than just the route of exposure, but defines the path from the source to exposure. For example, Evans et al. recently considered the case of exposure to TCE from dry cleaning [6]. In this case they described subpopulations as workers, consumers of dry cleaning, and residents. Although all of these populations were exposed through the inhalation route, the pathway for each sub-population is different (i.e. workers are exposed at the facility while consumers are exposed in their home from the chemical that remains on their clothing). Component intake fractions for these sub-populations could be summed to determine the total intake fraction.

Conclusion

Intake fraction is a simple, transparent, and potentially comprehensive measure of the relationship between emission and human exposure. It is arguably the simplest of all possible descriptions of the link between source emissions and population exposure. Although there is an inherent complexity in calculating the intake to all exposed individuals, expressing the result in terms of an intake fraction allows us to compress this complexity into an easily understood measure. The simplicity and non-dimensionality of the intake fraction facilitates the comparison of results among investigators in an easily understandable manner. Over time, we expect that a compendium of methods, case studies, and results will be assembled, including various release scenarios and pollutants. A compendium of such cased studies will provide an important resource for researchers and policy makers.

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Table 1. Summary of related terms

Term (reference)	Definition
Exposure efficiency [3]	The fraction of total production emissions that is likely to reach people, or the ratio of human intake to the amount emitted.
Exposure factor [4]	The ratio of total population exposure (μg m^{-3} person-year) to total emissions (tons)
Exposure effectiveness [5]	The fraction of released material that actually enters someone's breathing zone as measured in exposure units.
Exposure efficiency [1,6]	The fraction of material released from a source that is eventually inhaled or ingested.
Inhalation transfer factor [7]	The pollutant mass inhaled by an exposed individual per unit pollutant mass emitted from an air pollution source. The *population inhalation transfer factor* was defined as the sum of the inhalation transfer factors over all members of the exposed population.
Exposure constant [8]	The absorbed individual intake resulting from a unit release as calculated by the multimedia, multiple pathway exposure model USES [19].
Potential intake [9]	A multimedia source-to-intake factor based on the CalTOX multimedia model [20].
Population-based potential dose [10]	The exposure to a population for a unit emission source to a population based on the CalTOX multimedia model [20].
Fate factor [11]	A parameter "that enables the conversion of the emission flow into its related concentration increase" for transfers of an air-released substance to farm crops, then the rate of transfer to agricultural products, and finally the transfer into humans.

Figure 1.Applying Intake Factors: Benzene Intake From Cars And Environmental Tobacco Smoke

Motor vehicles are a major source of benzene emissions to urban air. Environmental tobacco smoke (ETS) contributes negligibly to urban-air benzene concentrations, but does contribute significantly to population dose, because the intake fraction for indoor air pollutant emissions is much larger than for outdoor emissions.

Consider California's South Coast air basin (SoCAB), which covers an area of 16,000 km^2. It is home to 14 million people who drive private vehicles approximately 0.5 billion km per day [21]. There are approximately 1.9 million smokers who consume 42 million cigarettes daily [22,23].

Sales-tax records indicate that 59 million liters of gasoline are consumed daily in cars and light / medium duty trucks [24]. Remote sensing and tunnel studies of motor-vehicle emissions indicate that tailpipe benzene emissions from motor vehicles average about 280 mg per liter of gasoline [24,25]. Thus, total SoCAB benzene emissions are estimated to be 17 tonnes / d from this source. Depending on meteorology, size, and population density, intake fractions for distributed urban air pollution sources lie in the range (1-500) × 10^{-6} [7]. Current efforts suggest that the average inhalation intake fraction for distributed sources of nonreactive, primary pollutants in SoCAB is ~ 40 × 10^{-6}.

Cigarette smoking in public buildings is not permitted in California. For the purposes of this example, we assume that 50% of cigarettes consumed in SoCAB are smoked in private residences. Average benzene emission factors for ETS are reported to be 280-610 µg per cigarette [26]. Using the midpoint of the range, total residential

emissions of benzene from ETS in SoCAB is estimated to be 9 kg / d, or about 0.6% of the emissions from motor vehicles. The intake fraction for indoor emissions of a nonreactive pollutant is estimated as the ratio of the occupant breathing rate to the building ventilation rate. For average conditions in California residences, this intake fraction is ~ 7×10^{-3}, almost 200 times as high as for outdoor emissions into this air basin.

Combining results, we estimate that the total inhalation intake of benzene for SoCAB residents is 700 g / d because of motor vehicle tailpipe emissions and 60 g / d from ETS. Thus, while the contribution of ETS to total benzene emissions into the air basin is entirely negligible, the contribution to inhalation intake is not.

Figure 2. Suggested notation for disaggregation.

We suggest that a qualifier describing the scenario be placed after *iF*, in parentheses. Authors should define any such qualifiers in the text in cases where such disaggregation is useful. For example, an author concerned about defining different intake fractions based on the route of exposure, the release media, and the subpopulation under consideration, could specify the intake fraction as follows:

iF (route, media, subpopulation)	The intake fraction to the population for a given route (i.e., inhalation, ingestion, dermal, total), media (i.e. release to air, water, soil), and subpopulation (i.e. workers, residents, all exposed).

Some of the qualifiers in the parentheses are components of the total intake fraction, such that they can be summed. For example, the intake fraction by each exposure route can be summed to obtain a total intake fraction, if multiple routes simultaneously expose the same population. So, the mathematical expression for exposure through all pathways could be written

$$iF(\text{total}) = iF(\text{inhalation}) + iF(\text{ingestion}) + iF(\text{dermal})$$