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# *Use of measurements in assessing doses to the public: a discussion paper*

*Steve Jones, Westlakes Scientific Consulting*

The views presented in this paper are those of the authors in consultation with members of NDAWG. They represent the views of the majority of members of NDAWG but do not necessarily reflect the views of the organisations from which the members are drawn.

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# 1 Introduction

This paper is intended as an aid to discussion of the issues involved in the use of measurements in making assessments of radiation doses to the public resulting from practices which involve the use of radioactivity, or sources of ionising radiation.

In principle, the use of measurements must always be preferred to reliance on the prediction of mathematical models; however the picture is complicated by the distinction between retrospective and prospective assessments, and by the very nature of the quantity which we are seeking to estimate.

For the purposes of radiation protection and environmental regulation, the quantity we usually need to estimate is the sum of the *annual effective dose from external irradiation* and the *committed effective dose from intakes of radionuclides during the year.* The external component is amenable to a number of fairly direct forms of measurement whereas the second component is not a measurable quantity, and can only be assessed indirectly from a combination of measurements, models and assumptions.

Moreover, we will usually be concerned with the contribution to this quantity from a specific practice (or a number of practices), net of the contribution both from natural background and, perhaps, from anthropogenic sources other than the practice or practices under consideration. This introduces further complications for the assessment of both internal and external exposure.

For the purposes of this paper, considerations are restricted to the issues directly concerned with the measurement of external radiation dose rates, concentrations of radionuclides in environmental media, and other quantities such as excretion rates or body burdens which relate to the estimation of radiation dose in a defined exposure scenario. The determination of individual habits and the construction of biokinetic models or dose per unit intake coefficients are not specifically considered.

# 2 Use of measurements in retrospective assessments

In retrospective assessments, we have access to the environment in which people have been exposed and therefore it is possible to make measurements which are related directly to the conditions of exposure which have been experienced. Assessments of this type are typified by the execution, and interpretation of the results from, routine environmental monitoring programmes carried out by site operators and the regulators.

## 2.1 Use of measurements in the assessment of annual effective dose from external irradiation

Broadly, there are two possibilities here. Monitoring instruments of various types may be used to measure radiation dose rates, or dosimeters of various types may be used to measure accumulated radiation dose, either to individuals or at specific fixed locations. In either case the monitoring device will measure *air kerma*, the absorbed dose or dose rate in air. Calibration of the device will be dependent on the energy spectrum of the gamma ray photons being measured and also the geometry of irradiation - whether the field is isotropic or directional. A conversion factor (which is dependent on photon energy and irradiation geometry) is required to convert air kerma into effective dose. Therefore, considerations in the use of the measurements include:

- Location: representative of exposure, including appropriate spatial and temporal averaging. Shielding factors are usually assumed for exposure within buildings.

- Choice of instrument or dosimeter: Response should be largely energy-independent, adequate sensitivity.
- Calibration standards: where necessary, appropriate to the nature of the radiation field being measured.
- Choice of air kerma to effective dose conversion factor.

Any assessment of external exposure should include an account of these considerations. In most circumstances, given sensible choices of instrument, calibration and kerma to dose conversion factor, the largest uncertainty in estimation is likely to be associated with spatial averaging and choice of shielding factors.

So far we have only considered assessment of the total dose. If we want to determine the additional dose due to a particular practice, background needs to be considered - and in most circumstances the total background will be comparable to, or substantially greater than, the dose rate from the practice. Neglecting for the moment the issue of other anthropogenic sources, it is helpful to consider background as comprising:

- Any intrinsic background response from the instrument.
- Response to cosmic rays.
- Response to natural terrestrial gamma rays (natural series radionuclides in soil, rocks and sediments).

Since the instrument background is independent of location, and the cosmic ray background may be considered so in the UK, these may be determined and subtracted from any measurement prior to consideration of background from terrestrial gamma rays.

The background from terrestrial gamma rays varies spatially according to the composition (and, possibly, geometry) of the substrate within a hundred metres or so of the point of measurement. Methods of determining it include:

- Measurements in uncontaminated areas of similar geology and/or sedimentology.
- Where the source of exposure from the practice is intermittent (eg, argon-41 plumes, external radiation from heat exchangers) the background may be measured directly at times when the source is absent.
- Energy dependent measurement - in situ gamma ray spectrometry.
- Detailed measurement of natural and anthropogenic radionuclides, including depth profiles, and use of radiation transport or shielding codes to calculate the magnitude of separate contributions.

None of these methods is entirely satisfactory and accurate assessment of contributions from a practice at levels at or below, say, 25% of background is not really practicable.

### 2.2 Use of measurements in the assessment of the committed effective dose from intakes of radionuclides during the year

#### *2.2.1 Ingestion: measurement of radionuclide concentrations in foodstuffs and water*

If the radionuclide content of an individual's diet can be determined, then annual intakes of radionuclides are straightforward to establish and committed effective doses may be assessed from standard dose per unit intake coefficients. Assessing the radionuclide content of diet is, however, not straightforward. Two broad approaches have been used.

- Measurement of radionuclide content of whole diet.

- Measurement of radionuclide content in individual dietary components.

Whole diet studies are complex to organise and demand a lot of co-operation from study subjects; they are more suited to research studies than routine surveillance programmes. Whilst they may potentially eliminate a number of the sources of uncertainty in assessments based on measurement of individual dietary components, they also have potential drawbacks. The results will not indicate the dietary components most important as a source of radionuclide intake; dilution of the important sources by uncontaminated foods may lead to limit of detection problems; and because the measurements usually only span a period of a month at most the results are susceptible to seasonal variation. Whole diet measurements are perhaps most useful as a means of confirming that surveillance based on individual dietary components is adequately representative, and that significant sources of intake have not been missed.

Routine surveillance programmes depend essentially on the measurement of radionuclides in foodstuff and drinking water. Key considerations are:

- Location/source: must be representative of the source of foodstuff actually consumed by the subject(s) of the assessment.
- Seasonality: where relevant, samples should take into account seasonal patterns in consumption.
- Sample replication: sample numbers should be sufficient to permit statistically sound treatment of variability.
- Species: must again be representative of what is actually consumed. Generic descriptions like 'fish' or 'mushrooms' may disguise a wide range of nuclide accumulation behaviour. Other factors such as the size or age of individual specimens may also be important.
- Sample preparation: must be consistent with the methods of handling and preparation for consumption. The portion or portions analysed should also match the portions of the sample which would actually be consumed.
- Analytical schedule: should determine all radionuclides likely to originate from the practice and make a significant contribution to committed effective dose. Analytical sensitivity should be sufficient to minimise limit of detection problems (see below).

Although this paper does not consider the assessment of habits, it is obvious from the above that information on the habits of the consumers being assessed is essential for proper and informed design of the sampling programme.

The interpretation of results from a sampling programme involves a number of steps which appear quite simple:

- Averaging the results to determine the annual average concentrations of radionuclides in each foodstuff.
- Multiplying average concentrations by consumption rates to determine annual intake.
- Use of dose per unit intake factors to assess committed effective dose.

Of course, there are a number of pitfalls and potential problems.

Conventionally, a simple arithmetic mean of all the sample results are taken. Some questions about this are:

- If there is seasonal variation in consumption, is it necessary to weight the sample average to replicate this?

- Is the arithmetic mean the best estimator of annual intake? If the data are not distributed normally, some other summary statistic of the data may be more meaningful (eg, the minimum variance unbiased estimate of the arithmetic mean for sparse lognormally distributed data).
- Are the results biased by limits of detection?

The assessment should include an estimate of the proportion of assessed committed effective dose which is accounted for by limits of detection. If this proportion is unacceptably high there are only a few possible remedies:

- Reduction of the limit of detection by improved analytical techniques, longer counting times and/or judicious use of sample bulking.
- If only a proportion of the samples are at the limit of detection, statistical methods based on the maximum likelihood principle may allow a better estimate to be made of the average concentration.
- More sophisticated statistical treatments may be feasible if counting result and confidence intervals (rather than limits of detection) are reported.
- Environmental models may be able to provide estimates of concentrations of a radionuclide which is below limit of detection, based on measured discharges or on positive measurements of the radionuclide in another foodstuff or an environmental medium such as water, soil or air. However the uncertainties in such estimates need to be recognised and, if possible, quantified.

#### *2.2.2 Inhalation (and immersion) - measurement of radionuclide concentrations in air*

Measurement of radionuclide concentrations in air for the purpose of dose assessment involves many of the same issues as discussed above for foodstuffs and water. Thus:

- Sampling locations should adequately represent the circumstances of exposure
- Sampling strategy should account for time variations in concentration in relation to timing of exposure (usually continuous sampling is appropriate, but this may not always be the case - eg, exposure may only occur during daylight hours)
- Analytical schedules should be adequately comprehensive, and limits of detection appropriate

Particle size selectivity is a particular issue in the interpretation of air sampling data. Most attention is usually paid to the 'respirable' fraction of the aerosol (<10 μm AMAD), which can reach the thoracic (bronchial and alveolar) regions of the lung. However, it should not be forgotten that the 'inhalable' fraction ranges up to about 100 μm AMAD, and particles in this size range can deliver dose to the extrathoracic airways. Particle size selective sampling is too complex (and demanding of analytical resource) for most routine surveillance, but ideally aerosol characterisation should play a part in the establishment of sampling methods.

Habits are less important in the dose assessment than is the case for intake by ingestion, since we can be sure that all individuals breathe and the breathing rates are reasonably predictable; however information on locations of exposure will be relevant. A common implicit assumption is that concentrations in indoor air will, over the long term, be equal to those in outdoor air. This has not often been tested, but appears to be a reasonable assumption for outdoor sources of airborne contamination.

Inhalation intakes are easily calculated from average concentrations in air and breathing rates. Committed effective doses follow from the use of dose per unit intake values; ICRP provide a number of dose per unit intake values for each radionuclide, depending on particle size and lung solubility behaviour. Where no specific information is available default values are recommended. Particle size information is relatively easy to obtain if necessary; lung solubility parameters are usually obtained from animal exposure experiments and this is rarely, if ever, attempted for environmental exposure situations.

### *2.2.3 Background in the assessment of committed effective dose from intakes*

Natural radionuclides make a substantial contribution to the committed effective dose from intakes, and their concentrations are subject to substantial spatial variation. Contributions of long-lived anthropogenic radionuclides such as $^{90}Sr$, $^{137}Cs$ and $^{239}Pu$ from sources such as atmospheric weapons testing and the Chernobyl accident may need to be distinguished from the contributions from the practice being assessed. Clearly, if the source under assessment releases only radionuclides for which there is no 'background' signal, background will not be an issue. However this will hardly ever be the case. Methods of estimating background contributions include:

- Measured levels from 'uncontaminated' areas, remote from the source under assessment. Clearly this must be used with care and with consideration for the possible spatial variation in the 'background' levels.
- Isotope ratio 'fingerprints' such as the $^{134}Cs$:$^{137}Cs$ and $^{238}Pu$:$^{239,240}Pu$ ratios can be very helpful in distinguishing the contributions from different sources of contamination.
- Environmental modelling may assist in establishing the relative contribution of different sources.

Determination of 'background' contributions will rarely be definitive and, if measured contributions are comparable with background levels, determination of contributions from the source under assessment are likely to be rather uncertain.

## 2.3 Measurements on exposed individuals

The maxim of reliance on measurements would suggest that some form of measurement on exposed individuals would provide the most secure means of dose assessment. Unfortunately, things are not quite as simple as that, for both practical and scientific reasons. The possibilities include:

- Issue of dosimeters to individuals for the measurement of external exposure.
- Use of whole body monitoring, urinalysis, and/or faecal analysis to assess the internal exposure of individuals.
- Analysis of tissue samples to assess internal exposures.
- Determination of radon or thoron exhalation to estimate lung burdens of U and Th series radionuclides.

Use of dosimeters: This is quite practicable as a means of assessing total external exposures, although limits of detection may be an issue. However the problem of background subtraction (taking account of the spatial variation in background) will be substantial.

Whole body monitoring: This measures the total body burden at the time of measurement; as such it cannot be used directly to assess the committed effective dose from intakes during the year. Detection sensitivity limits its effectiveness, although it has been used successfully for the determination of nuclides such as $^{137}Cs$ in exposed individuals. Its main application has been in reassurance monitoring for concerned individuals.

Urinalysis and faecal analysis: These techniques measure a combination of accumulated body burden and recent or current intake rates (for urinalysis, more precisely uptake rates to blood). Interpretation relies on application of biokinetic models to link intakes to excretion rates, and also some assumptions about the history of exposures. Limits of detection are also likely to be an issue for application to environmental exposures.

Analysis of tissue samples: The principal option here is determination of radionuclide concentrations in samples of tissue taken at autopsy; this has not often been done for environmentally exposed individuals, and stricter requirements for consent would now make such studies rather difficult. Analysis of children's milk teeth, or teeth extracted for orthodontic purposes, avoids such difficulties and a few studies have used this approach. The analysis determines the concentration of radionuclides in the organ analysed at the time of sampling. Interpretation in terms of intake rates would involve use of biokinetic models and assumptions about exposure history in a similar way to urinalysis and faecal analysis.

In practice, measurements on people play little or no role in routine surveillance programmes. The main use of this type of measurement is in the confirmation that assessments based on measurements of radionuclide concentrations in environmental media are producing reasonable results, and are not missing significant sources of exposure - an example being the whole body monitor measurements of $^{137}$Cs levels in Seascale residents. They have also been used to confirm some of the parameters used in dose assessments - for example, urinalysis applied to volunteers consuming shellfish to estimate gut uptake factor for plutonium and technetium.

Although not directly related to dose assessment, epidemiological studies on exposed populations provide a direct means of assessing the health of the population, which is the end objective of human radiological protection. A full discussion of epidemiology is outside the scope of this paper. Interpretation of epidemiological findings is complicated by the need for careful statistical analysis and the difficulties of unambiguously determining causative factors if and when statistically significant deviations from expected disease incidence are found. Epidemiological studies of the atomic bomb survivors in Hiroshima and Nagasaki, and of a number of other highly exposed populations, have contributed greatly to our knowledge of radiation risks. Epidemiological studies of environmentally exposed populations have from time to time prompted some searching examination of the methods for estimation of doses to the public from environmental measurements.

## 3 Use of environmental measurements in prospective dose assessments, and in dose reconstruction

In prospective dose assessments, the circumstances of exposure have not yet occurred so clearly any form of measurement is not possible. In dose reconstruction, the circumstances of exposure lie in the past; some measurements may be available, but these may not cover all of the radionuclides or all of the pathways which are considered relevant. In these cases concentrations in environmental media are usually predicted, or reconstructed, by use of models.

Measurements, nonetheless, have an important role because they may be used to calibrate or validate the models being used. A full discussion of the use of measurements in the development, calibration and validation of models would be very extensive. The scope of measurements which may be relevant is much wider than that applicable simply to the assessment of doses from current levels of environmental contamination; in outline:

- The type of measurements in environmental media described above, especially if available in the form of consistent time series over many years, can help build confidence in models which relate discharge rates to environmental contamination levels. The models may then be used with greater confidence to extend the measurement series either spatially or temporally, based on expected future discharges (or recorded past discharges).
- A much wider range of measurements will be relevant to helping derive parameters which describe the environmental processes encoded by the models. Thus a wide range of environmental characterisation measurements, not all of which would involve the measurement of radionuclide concentrations, may need to be considered. Examples include the determination of tidal flows and residual currents; sedimentation rates and suspended sediment loadings; atmospheric dispersion categories, deposition rates and interception coefficients for airborne particulates; transfer coefficients for radionuclides between a range of environmental media; chemical speciation of radionuclides (particularly important for elements such as hydrogen, carbon and iodine) and many others.
- Standard values (or ranges of values) for many of the necessary parameters are available from the literature, but confidence in the results of model predictions is greatly increased by the availability of relevant site-specific data.

## 4 Possible areas for further attention

Current approaches for the design of surveillance programmes and the interpretation of results are well established and generally sound. Areas which may benefit from some attention include:

- Ensuring clarity of definition of measurement and calibration methods, and any underlying implicit assumptions, when reporting results.
- Addressing the tension between the need for comprehensive sampling programmes, including adequate sample replication and extensive radio-analytical requirements, and cost. Fulfilling all of the criteria discussed in this report would be hard to justify when the doses being assessed are of the order of tens of microsieverts per year; nonetheless adequate surveillance is necessary. Compromise sampling strategies involving, for example, combining prepared samples from a number of food groups prior to analysis may be a way forward.
- Developing criteria for ‘when not to monitor’ - ie, when concentrations are below limits of detection, when assessed contributions to dose are very low, when models can give adequate assurance that monitoring is not justified.
- Greater attention to the definition of background - this becomes increasingly important as contributions from practices decrease.
- Defining the most appropriate methods of averaging sparse data, and quantifying variance and uncertainty in the resulting estimate of the mean.
- Improving the extent to which model predictions can be supported by measured site specific parameters or measured validation data.