Recent advances in animal radioecology and mitigation of animal product contamination after accidents

B. J. Howard, N. A. Beresford and G. Voigt*

Centre for Ecology and Hydrology-Merlewood, Grange-over-Sands, Cumbria, LA11 6JU, UK

**Agency's Laboratories Seibersdorf, Wagramer Strasse 5, P.O.Box 100A-1400, Vienna, Austria*

Abstract: Recent research has led to significant progress in our understanding of factors controlling transfer of radionuclides to animals and in the development of countermeasures for reducing contamination of animal products. Improved understanding has led to the development of more mechanistically based models for some radionuclides, which take account of stable or analogue interactions. The potential advantages of the development of generic approaches, dispensing with divisions into species, or even radionuclide, are discussed and constitute a significant area for future development. The advances have improved our knowledge of the effectiveness of a range of countermeasures and allowed potentially inappropriate measures to be identified. For radiocaesium in particular, effective and feasible countermeasures have been identified and successfully implemented over the years following the Chernobyl accident. However, countermeasure effectiveness is not the only consideration. In addition, cost and criteria such as availability, technical feasibility, acceptability and environmental and social side effects need to be taken into account. Evaluation of these factors has shown that some previously recommended countermeasures are unlikely to be feasible in Western Europe.

1. INTRODUCTION

Contamination of animal products is often a major contributor to ingested radiation dose from both routine and accidental releases. Animal products were the major agricultural food type requiring intervention outside of the former Soviet Union after the Chernobyl accident and in some countries radiocaesium countermeasures are still being used [1]. An understanding of the factors affecting the transfer of radionuclides to, and their behaviour in, animals is therefore essential if we are to be able to interpret monitoring results, accurately predict activity concentration in animal derived food products and develop effective and appropriate countermeasures.

This paper summarises recent advances in animal radioecology and the development and usefulness of countermeasures for radiocaesium, radioiodine and radiostrontium in animal products. It is based on two recent reviews [1.2].

2. TRANSFER OF RADIONUCLIDES TO ANIMALS

Ward *et al.* [3] introduced the transfer coefficient as a parameter to describe the transfer of radiocaesium from the diet to the milk of dairy cattle. The transfer coefficient (F_m) was defined as the equilibrium ratio between the radionuclide activity concentration in the animal product and the daily radionuclide intake. Transfer coefficient values exhibited less variability between individual animals (within the experimental herd) than simply expressing transfer as the total amount of Cs excreted in milk expressed as a percentage of intake. The transfer coefficient was adopted as the basis for quantifying transfer to both milk (F_m) and meat (F_f) for all radionuclides and single values were recommended for each radionuclide/animal product combination. Their validity for radionuclides with long biological half-lives (e.g. Pu, Am, Cd) has been questioned since equilibrium will not be established within the lifetime of the animal [4]. Furthermore, it has been demonstrated that many factors affect transfer coefficients, especially for radiocaesium. Differences of over two orders of magnitude in transfer coefficients to the milk and meat of ruminants have been reported for different environmental dietary sources, including soils, sediments, milk (for suckling lambs) and fungi; Furthermore, Voigt *et al*. [5] noted differences in radiocaesium transfer coefficients to hen eggs and meat between contaminated wheat and grass pellet diets. Variation in transfer coefficients has been explained by metabolic factors including homeostatic control, dietary intake rates [6], lactation [7] and exercise [8]. Variation in radiocaesium transfer coefficients was subsequently noted in the International Atomic Energy Agency handbook of transfer parameter values [4], but no recommendations were given to accommodate this variation within radiological assessments. Examples of the impact of some of these factors are given below.

2.1 Homeostatic control

The recommendation of single transfer coefficient values for radionuclides which are either themselves, or through a stable analogue, subject to homeostatic control is inappropriate (eg radiostrontium [9], radioiodine [10,11] and tritium [12]). However, relationships can be derived to enable transfer coefficients to be estimated for such radionuclides which allow for the effect of metabolic control.

Dietary intake rate of calcium influences the rate of radiostrontium transfer to milk. A relationship between dietary calcium intake and radiostrontium transfer coefficient for milk (F_mSr) has been derived recently [9, 13] of the form:

{Equation 1}

$$F_mSr = \frac{0.11 \times [Ca]_{milk}}{I_{Ca}}$$

where $[Ca]_{milk}$ the concentration of calcium in milk (g kg^{-1}); I_{Ca} the daily intake of calcium (g d^{-1}) and 0.11 is the observed ratio of the discrimination in the transfer of strontium from the diet to milk compared with that of calcium [14], which is a constant for all mammals.

A comparison of the predicted values with observed data for dairy ruminants is shown in Figure 1. Previously recommended F_m values (e.g. [4]) are inappropriate for agricultural feeding regimes in most Western European countries since they correspond to low levels of calcium intake.

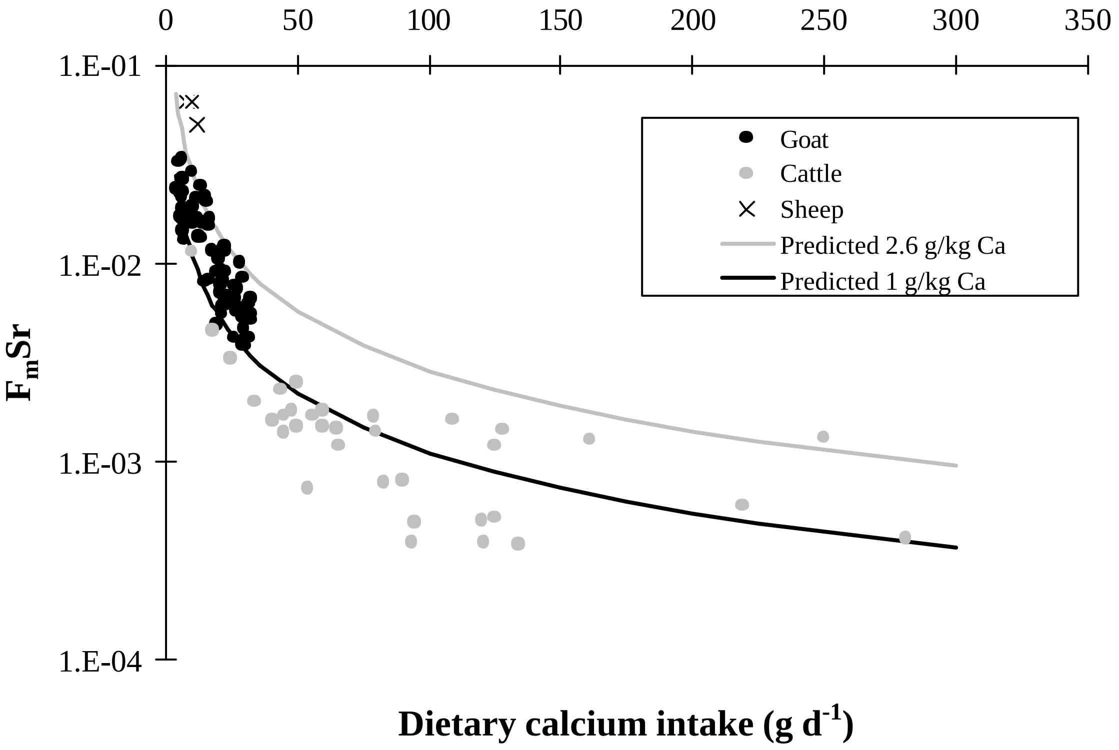

Figure 1. Comparison between calcium intake and F_m for strontium [2]. The lines represent predicted values from Equation 1 based upon calcium contents in milk of 1 g kg^{-1} (typical for cattle) and 2.6 g kg^{-1} (typical for sheep) respectively.

Because of the relationship between calcium and radiostrontium, the transfer of radiostrontium to milk is reduced if the calcium intake increases, although the reduction will depend on the animal's basal calcium intake and status. In general terms, if the dietary intake of calcium is doubled then the radiostrontium activity concentration in milk would be halved. Larger reductions would be achievable in those animals with low dietary calcium intakes prior to calcium supplementation.

Iodine is an important trace element required by the thyroid for hormone synthesis, and the metabolism and excretion of radioiodine is controlled by an individual's stable iodine status. Transfer of iodide to both the thyroid and mammary glands is an active process [15] which is saturable at high iodide plasma concentrations. This results in a change in F_m for radioiodine with varying stable iodine intake (Figure 2). The effect can be explained by considering the relative transfer of iodide to the thyroid and mammary gland. As the stable dietary iodine increases, the proportion of the daily radioiodine intake which is transferred to the thyroid declines because of the constant rate of uptake of iodide by the thyroid. Thus, a smaller fraction of the daily iodide intake (both stable iodine and radioiodine isotopes) is transferred to the thyroid and the proportion available for transfer to the mammary gland increases. At high stable iodine daily intakes, this effect is offset by saturation of the transfer from plasma to milk and the transfer of radioiodine to milk declines.

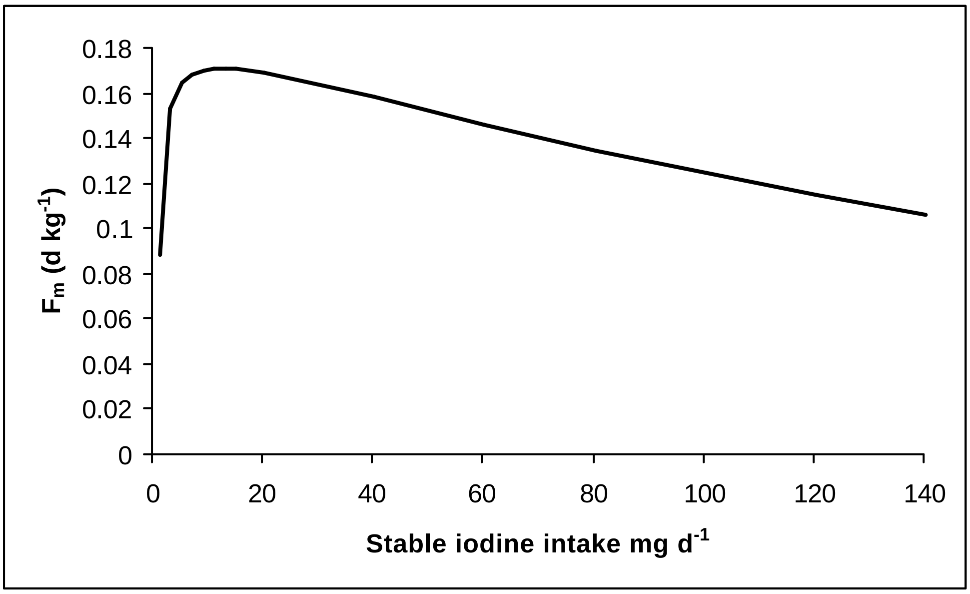

Figure 2. Predicted variation in radioiodine transfer coefficient with varying stable iodine intakes in dairy goats; stable iodine intake rates include those representative of those prevailing under normal practice (1-20 mg d^{-1}) to the maximum tolerable advised intake for ruminants (50 mg kg^{-1} dry matter) using the model described by Crout *et al*. [10].

Conceptually, transfer coefficients might be thought to be inappropriate for radionuclides of elements which are integral components of biota such as C and H. However, by modelling the hydrogen balance within animals, Galeriu *et al.* [12] have developed an approach based on a simplified understanding of hydrogen metabolism whereby transfer coefficients can be estimated for any food-producing animal under different physiological conditions (e.g. lactating, live-weight) for both organically bound tritium and tritiated water. Predictions compare well to the available data and demonstrate the inappropriateness of species specific transfer coefficients, as recommended by many bodies for ^{3}H [4, 16,17].

2.2 Absorption and bioavailability

Some authors have suggested that differences in transfer coefficients were due to differences in bioavailability. The true absorption coefficient (A_t) can be defined as the fraction of ingested radionuclide that is transferred across the wall of the gut and it takes endogenous secretion of radionuclides into the gut into account. Methodologies to estimate A_t are reviewed by Mayes *et al.* [18] and Beresford *et al.* [19]. For radionuclides with more than one isotope, a different isotope to that present in the diet can be injected into the animal's blood to allow the direct estimation of endogenous faecal excretion or the rate of uptake from the diet into the plasma (by comparing isotopic ratios). Measurements of true absorption have shown that differences in radiocaesium transfer coefficients between animals of varying ages are not due to variation in absorption across the gut [20].

For radioiodine, absorption is complete regardless of the source or dietary stable iodine intake [19]. In contrast, for radiocaesium the source ingested is a major factor with A_t values derived for environmental sources ranging from <0.10 to >0.80 [19]. Although variation in absorption values have been measured for radiostrontium, the extent of absorption from a given source is largely controlled by the animal's calcium intake and requirement (see above). Under normal levels of calcium intake, the source of radiostrontium ingested is unlikely to influence the levels in milk or tissues to any great extent [19].

2.3 Generic approaches to quantifying transfer

The advantages of common models to describe the behaviour of radionuclides in different animals was recognised by Stara *et al.* [21] who demonstrated relationships between the long component of biological half-life of radiocaesium and live-weight. Recently, Nalezinski *et al.* [22] derived expressions between live-weight and radiocaesium transfer coefficients from a (limited) compilation of literature data; separate expressions were derived for ruminants and monogastrics (comprising hens and pigs). Similarly, models for radioisotopes of a number of heavy metals have been capable of predicting activity concentrations in dairy cattle by adjusting the model rate coefficients by the ratio of the metabolic live-weights of sheep and cattle [23; 24]. However, Beresford *et al.* [6] found that variation in radiocaesium transfer to muscle of individual sheep (including pregnant and lactating adults, and growing lambs) could not be explained by differences in live-weight. Variation was well explained by relationships derived between dry-matter intake and F_f and Beresford *et al.* [6] have demonstrated that this relationship can be expanded to other ruminants.

There have been recent developments of more generic models of a number of other radionuclides. Crout *et al.* [25] suggested a model describing the transfer of ^{3}H, ^{14}C and ^{35}S to sheep tissues based upon a simplified representation of processes such as protein synthesis and degradation, and respiration so that individual radionuclides shared many common parameter values. Whilst the models described the experimental data on which they were parameterised well, their applicability is currently limited to animals under similar management and physiological conditions. However, models for these radionuclides based upon a metabolic understanding have great potential as they could predict the influence of dietary intake, physiological status and form of radionuclide within the diet. The concept has recently been applied to the prediction of transfer coefficients for ^{3}H in food producing animals by Galeriu *et al.* [12] as discussed above. More recently, the same authors have defined mass dependent relationships for OBT and carbon loss rates across a range of mammalian species [26].

These recent developments represent potentially useful methods of predicting the transfer of radionuclides to animal derived food products or to wild animals for application in environmental impact assessments [27]. However, the work is being conducted largely as desk studies with little current experimental validation. For instance, there are no experimental data with which to compare the predictions of the model of Galeriu *et al.* [12] for ^{3}H concentrations within poultry.

2.4 COUNTERMEASURES FOR ANIMAL PRODUCTS

There has been significant recent progress with respect to countermeasure techniques. The focus has been not only on effectiveness, but also on other issues such as cost, acceptability (to stakeholders and society) and practical considerations (e.g. availability, feasibility and side-effects) [28, 29; 30]. Furthermore, the improved mechanistic understanding of the behaviour of radionuclides in animals outlined above has allowed the effect of some countermeasures to be incorporated into predictive models [10,25]. Current conclusions expressed by Howard *et al*. [30] on appropriate countermeasures for the three most important radionuclide contaminants of animal products are briefly given below.

2.4.1 Radioiodine

Contamination of milk by short-lived radioiodine isotopes is a major source of potential ingested exposure after many types of nuclear accident. It is therefore important that emergency preparedness plans for this eventuality are well informed and appropriately focused.

Previous recommendations in the literature regarding the administration of stable iodine to reduce radioiodine activity concentrations in milk are probably unjustified: the reduction achieved is only two to three fold and there are significant side effects in that the stable iodine in milk would probably exceed acceptable limits [10]. Furthermore, there may be problems in obtaining, distributing and administering suitable iodine sources within the time scale required. The most effective and practical solution remains the provision of uncontaminated feed (clean feeding) to animals, but the availability of suitable stocks of feedstuffs will vary seasonally.

Storage of contaminated milk or conversion to other storable products would be another effective option, but may not be commercially or socially acceptable and would need to take account of other radionuclides also present. Prior arrangement for this option with relevant organisations and commercial concerns would be beneficial.

2.4.2 Radiocaesium

Condemnation of meat is an immediately available and effective countermeasure to reduce ingested dose from animal products. This was a widely used countermeasure after the Chernobyl accident, but this was expensive and resulted in large quantities of contaminated waste. It was therefore not considered to have been a good solution and clean feeding would have been a better alternative.

The most useful, and in the aftermath of Chernobyl, widely used countermeasures for radiocaesium contamination of animals were clean feeding, the administration of hexacyanoferrates (feed additives which reduce radiocaesium absorption from the gut), changing slaughter times, pasture improvement/management and use of live-monitoring. Hexacyanoferrate compounds are highly effective with reported reduction factors of up to 10 in the former Soviet Union [31] and have low toxicity [32]. They can now be incorporated into many different delivery systems for use in different farming systems and for different species. Cost effectiveness has been found to be good in certain situations, and for free ranging animals, ammonium hexacyanoferrate (AFCF) containing rumen dwelling boli are more cost effective than clean feeding, although they are somewhat less practical for reindeer than other ruminants. The public acceptability of using AFCF in the farming community is a factor which needs consideration; some delivery methods are less intrusive than others. Furthermore, the lack of a commercial manufacturer of boli would currently restrict their use in the event of a nuclear accident and the long term licensing of AFCF as an animal feed additive within the EU is currently unclear.

2.4.3 Radiostrontium

The implication of Equation 1 and Figure 1 is that increasing dietary calcium intake will effectively reduce the transfer of radiostrontium to milk. However, there is a limit to the potential effectiveness of calcium supplementation because of interference with availability of other essential nutrients. For animals receiving basal dietary calcium levels typical for Western Europe, a doubling of calcium intake is recommended with an anticipated reduction of 40-60% in the transfer of radiostrontium to milk [33]. However, it may be possible to increase its effectiveness on the basis of farm-specific assessments.

Currently, the use of binders to prevent gut uptake of radiostrontium cannot be recommended because: (i) many are ineffective, (ii) alginates are effective but are currently too expensive and (iii) some potentially effective binders have possible side effects which have been inadequately tested. Soil treatment or soil amendments to reduce radiostrontium concentrations in animal fodder provide a viable and practical alternative to animal-based countermeasures for radiostrontium.

2.4.4 Discussion

The usefulness of various countermeasures and assessment of whether they are realistically likely to be useful and effective for contamination of animals will vary with many different factors, both within and between countries, including:

- Severity of contamination
- Importance of affected areas to national economies
- Type of ecosystem affected and existing management systems
- Priority given to maintaining existing ways of life
- Animal species and products contaminated
- Availability of suitable waste disposal options
- Way of life
- National economy
- Legal and administrative framework

It is clear that suitable countermeasures are likely to vary considerably between different areas and communities, and national authorities need to evaluate their own relevant criteria. Such assessments will need to be reviewed to cope with future changes such as feeding regimes of agricultural animals.

Contamination of animals and their products is likely to be the major route of exposure via the foodchain in the event of an accident and may give rise to considerable public concern. Some problems and potential solutions with regard to contamination of animals would benefit from prior consideration and agreement with relevant stakeholders, such as that ongoing within consultation groups in the UK [34] and Europe (www.ec-farming.net). Such bodies would include organisations who do not necessarily have a direct regulatory role regarding nuclear issues, but which would or might be involved in dealing with the consequences of accident, such as farmers unions, the dairy industry and consumer bodies.

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