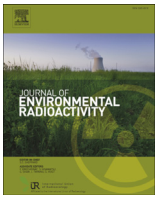
Journal of Environmental Radioactivity 142 (2015) 136–151

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad



Review

Review of Russian language studies on radionuclide behaviour in agricultural animals: biological half-lives

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ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form
16 January 2015
Accepted 16 January 2015
Available online 17 February 2015

Keywords:
Biological half-lives
Cattle
Sheep
Goat
Hens
Radionuclides

ABSTRACT

Extensive studies on transfer of radionuclides to animals were carried out in the USSR from the 1950s. Few of these studies were published in the international refereed literature or taken into account in international reviews. This paper continues a series of reviews of Russian language literature on radionuclide transfer to animals, providing information on biological half-lives of radionuclides in various animal tissues. The data are compared, where possible, with those reported in other countries. The data are normally quantified using a single or double exponential accounting for different proportions of the loss. For some products, such as milk, biological half-lives tend to be rapid at 1–3 d for most radionuclides and largely described by a single exponential. However, for other animal products biological half-lives can vary widely as they are influenced by many factors such as the age and size of the animal. Experimental protocols, such as the duration of the study, radionuclide administration and/or sample collection protocol also influence the value of biological half-lives estimated.

1. Introduction

Assessments of the routine releases of radioactivity to the environment are often based on equilibrium models (e.g. IAEA, 2001). Therefore, transfer coefficients defined as the equilibrium ratio of the radionuclide activity concentration in specific animal tissues (such as milk and meat) divided by the daily intake of the radionuclide at equilibrium have been collated by many international reviews (IAEA, 1994, 2010; Howard et al., 2009a,b). Such parameter values have, by definition, some limitations as they are not directly applicable to dynamic situations, such as assessments of the consequences of radiological accidents or pulse releases.

In the last century, access to the data available from the Russian language sources was largely limited to a few monographs published in English, restricting the worldwide use of a substantial amount of information. To address this deficiency, we have previously collated, assessed and discussed Russian language studies on radionuclide gut absorption, radionuclide transfer to milk, meat and poultry (Fesenko et al., 2007a,b; Fesenko et al., 2009a,b).

Extensive studies on the transfer of radionuclides to farm animals were started in the USSR in the mid-1950s mainly in areas affected by the 1957 Kyshtym accident with a series of controlled experiments using a single administration of radionuclides. The main purpose of the research was to support dosimetric studies for the interpretation of biological effects of ionizing radiation following a pulse deposition of high activities of radionuclides. A secondary aim was to assist in the development of countermeasures and remedial actions for animals, notably including feeding animals with clean fodder, for which it is essential to have access to data on excretion rates of radionuclides from the body of animals.

Many models aiming to simulate dynamic accumulation and excretion of radionuclides in farm animals and their products use biological half-lives ($T^b_{1/2}$) together with transfer coefficients (IAEA, 2009; Müller and Pröhl, 1993; Brown and Simonds 1995).

Biological half-lives are defined as the time required for a given concentration of radionuclides in a tissue or an animal product, such as muscle, thyroid or milk, to reduce to half its original concentration by processes excluding physical decay.

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http://dx.doi.org/10.1016/j.jenvrad.2015.01.015
0265-931X/

Table 1
Details of references sources for effective biological half-lives in animals. Age and liveweight are given at the beginning of radionuclide administration.

Reference	Experimental details and data analysis
Cattle	
Annenkov (1964a).	*Target radionuclide*: ^{90}Sr. *Target product*: milk. 10 dairy cows of 450–500 kg liveweight, aged 5–6 y, with milk yield of 10–13 l d^{-1} chronically exposed to ^{90}Sr in hay from areas highly contaminated following the Kyshtym accident for 150 d. Milk samples were taken throughout and after cessation of feeding with the contaminated feed.
Annenkov (1969).	Doctor of biological science thesis. Review of own experiments on radionuclide transfer to various animals carried out between 1961 and 1968. Data on biological half-lives are provided for cattle, pigs, rabbits and rats.
Astasheva et al. (1991).	*Target radionuclide*: ^{137}Cs. *Target tissue*: muscles. Field clean feeding experiment with 25 bulls (aged 18–20 m; liveweight of 430–480 kg), 25 heifers and 25 cows (unknown age).
Fedorov et al. (1973).	*Target radionuclides* - 10 days old fission products: ^{89,90}Sr, ^{95,97}Zr, ^{99}Mo, ^{103,106}Ru, ^{132}Te, ^{131,133,135}I, ^{140}Ba and ^{141,144}Ce administrated as nitrate. *Target product*: milk, muscle, liver, kidney, skeleton, blood, urine, thyroid. Single oral administration. Forty 4–7 y old dairy cows with milk yield of 7.1 l d^{-1} and average liveweight of 472 ± 23 kg. Animals were sampled at intervals up to 12 d after dosing and radionuclides activity concentrations in specified tissues measured. Samples of blood and milk were taken every 3 h after the experiment commenced until the first slaughtering at 12 h after administration. Some additional information on this study is presented in Prister (2008).
Iliazov (2001).	*Target radionuclide*: ^{137}Cs. *Target tissue*: muscles. Field clean feeding experiment with young bulls aged 10–12 m with liveweight of 340–380 kg
Korneyev and Sirotkin (1970).	*Target radionuclide*: ^{131}I. *Target product*: milk. Two cows aged 5 and 7 y, liveweight 455–500 kg and milk yield of 9–10 l d^{-1}. Single oral administration of iodine as KI solution. Samples taken 1, 6, 12 and 24 h after dosing and thereafter each 12 h for 10 days after iodine administration.
Korneyev et al. (1989).	*Target radionuclides*: ^{45}Ca, ^{90}Sr, ^{137}Cs. *Target tissues:* milk, blood, urine, faeces. Short-term experiment with 4–8 y old cows given a single oral administration. Liveweight of 470 ± 20 kg and milk yield of 10 ± 2 l d^{-1}. Radionuclides were administrated as a chloride, pH of c. 3.
Kudryavtsev and Sirotkin (1991).	*Target radionuclide*: ^{137}Cs. *Target tissue*: milk. 100 cows aged 4–6 years with liveweight of 400–500 kg from the farm located in area contaminated by the Chernobyl experiment were involved. Twenty cows selected randomly were taken for indoor feeding with low contaminated silage and the remaining 80 cows were grazing contaminated grass outdoors. ^{137}Cs measured daily for 10 d thereafter.
Panchenko et al. (1974).	*Target radionuclide*: ^{90}Sr. *Target tissues*: muscle, skeleton. Summary of a large-scale experiment with chronic oral administration of $^{90}SrCl_2$ to 189 calves aged 180–540 d with liveweight of 400–450 kg. Other details of the experiment were not given.
Sirotkin et al. (1969).	*Target radionuclide*: ^{90}Sr. *Target product*: milk. Five cows aged 9–10 y, liveweight of 360–490 kg and milk yield of 8–9 l d^{-1}. Single intravenous administration of strontium. Milk samples taken daily during 330 days after strontium administration. Animals were fed with the feeds containing 40 g (control) and 16 g of calcium per day.
Sirotkin et al. (1972a).	*Target radionuclide*: ^{131}I. *Target tissues*: milk, thyroid, blood, excreta. Six dairy cows aged 4–5 y, liveweight of 380–520 kg, milk yield of 7–10 l d^{-1} were involved in the experiment. Three cows orally administered ^{131}I incorporated within feed by surface dispersion of aqueous Na^{131}I and three cows were directly administrated aqueous Na^{131}I. Samples were taken 2 and 6 h on the first day following administration and thereafter over 8 d with intervals of 11–14 h. Half-lives for excreta were not calculated.
Sirotkin et al. (1972b)	*Target radionuclide*: ^{137}Cs. *Target tissues*: muscle, skin, skeleton, blood, offal, excreta. 21 calves with 36 ± 5 kg liveweight given chronic (300 d) oral administration of ^{137}Cs and sampled 1, 5, 10, 30, 60, 150 and 300 d following cessation of ^{137}Cs administration.
Sirotkin and Sarapul'tsev (1973).	*Target radionuclides*: ^{45}Ca, ^{90}Sr, ^{95}Zr, ^{106}Ru, ^{131}I, ^{137}Cs, ^{140}Ba, ^{144}Ce. *Target product*: milk. Nine-day experiment with single oral administration of aqueous solution of Na^{131}I to 10 dairy cows aged 4–17 y with liveweight of 338–500 kg and milk yield of 7–10 l d^{-1}. Samples were taken after 1, 6, 12 and 24 h following radionuclide administration and then every 12 h starting from the 2 d for 8 d.
Sirotkin et al. (1976).	*Target radionuclides*: ^{90}Sr and ^{137}Cs. *Target tissues:* muscle, skeleton. Sixty three new-born calves with liveweight of 33 ± 0.9 kg were orally administrated of ^{90}Sr and ^{137}Cs for 60 d (group 1), 150 d (group 2) and for 300 d (group 3). The animals were slaughtered and samples were taken at 1, 5, 10, 30, 60, 150 and 300 d following cessation of radionuclide administration.
Sirotkin et al. (1978).	*Target radionuclides*: ^{90}Sr, ^{131}I, ^{137}Cs. *Target tissues:* Muscle, liver, skeleton. Summary of a large programme of studies with single administration of radionuclides to adult animals aged 740–2500 d with liveweight of 420–510 kg. Radionuclides were orally administered as a chloride except for I for which KI solution was used.
Sirotkin et al. (1980).	*Target radionuclides*: ^{59}Fe, ^{60}Co. *Target tissues*: blood, milk. 10 dairy cows with 430–480 kg liveweight, aged 6–8 y, with milk yield of 8–11 l d^{-1} Radionuclides orally administrated as a chloride
Sirotkin (1987).	*Target radionuclides*: ^{131}I and ^{137}Cs. *Target tissues:* lung, liver, kidney, skin, muscle, heart, blood, spleen. 13 new born calves and 22 calves aged 5 m (40–45 kg liveweight) and 10 m (300–350 kg liveweight) at the start of experiment given a single oral ^{137}Cs administration. Tissues ^{137}Cs activity concentration measured over a one year period. Data of experiment with ^{131}I and ^{137}Cs transfers to muscles of cows are also presented without details of the experimental design.
Sheep	
Abramova et al. (1984).	*Target radionuclide*: ^{65}Zn. *Target tissue*: blood. Samples taken from 3 adult animal Tzigay breed sheep (liveweight 42–46 kg) 1, 4, 8, 12, 24, 48, 96, 120 and 240 h following oral chronic administration of aqueous $^{65}ZnCl_2$.
Buldakov (1961).	*Target radionuclides*: ^{90}Sr, ^{137}Cs, ^{144}Ce. *Target tissues*: muscle, liver, kidney, skeleton. The study was chronic oral administration of ^{90}Sr, ^{137}Cs and ^{144}Ce to 78 sheep ($n = 9$-Ce, $n = 20$-Cs $n = 49$-Sr) aged ~3 years with liveweight of 45–52 kg for 300 d. The second study was single administration of the same radionuclides. Samples were taken and measured up to 450 d after radionuclide administration. Half-lives are reported mainly for bone and muscle.
Buldakov (1964).	*Target radionuclide*: ^{137}Cs. *Target tissues*: muscle, liver, kidney, skeleton. Presented data on two experiments. Experiment with chronic oral administration of ^{137}Cs of 28 adult sheep aged 1.5 year with liveweight 40–46 kg. Samples were taken 1, 4, 9, 30, 60, 180 and 350 d after the cessation of radionuclide administration. The second experiment studied ^{137}Cs loss from muscles of 15 lambs obtained from contaminated sheep. Samples were taken at the birth and at 30, 60, 90 and 120 d after the birth.
Buldakov and Burov (1967).	*Target radionuclide*: ^{144}Ce. *Target tissues*: liver, bone. Data from several different experiments are given. Animals of three age groups (aged 20–25 d (liveweight of 12–16 kg), 180–200 days (liveweight of 36–42 kg) days and 530–540 days (48–54 kg liveweight) were orally administered as $CeCl_2$. The first two groups given a single oral administration were sampled after 1, 4, 8, 16, 31, 64 and 128 d. A third group (12 animals) were chronic oral administration $CeCl_2$ for 1140 d. Animals were sampled 18, 105, 300 and 1140 d after the beginning of the experiment. Half-lives are calculated only for first two groups and are given for lamb and ewes separately.
Panchenko et al. (1974).	*Target radionuclide*: ^{90}Sr. *Target tissue*: muscle, bone. Summary of a large scale experiment with chronic oral administration of ^{90}Sr chloride to 175 sheep aged from 3 to 1100 d with liveweight of 42–54 kg. Other details of the experiment were not given.
Sirotkin et al. (1978).	*Target radionuclides*: ^{90}Sr, ^{137}Cs, ^{144}Ce. *Target tissues*: muscle, liver, bone. Summary of a large number of studies with adult animals aged from 270 to 1100 d with liveweight of 44–48 kg. Radionuclides were orally chronically administered as a chloride.
Sirotkin (1987).	*Target radionuclide*: ^{137}Cs. *Target tissue:* muscle. Summary paper. Data of experiment with ^{137}Cs transfer to muscles of sheep aged 80–90 d at the time of administration are presented without further details of the experimental design.
Goats	
Sirotkin et al. (1978).	*Target radionuclides*: ^{90}Sr, ^{106}Ru, ^{137}Cs. *Target tissues*: muscle, bone. Summary of a large number of studies with adult goats aged from 320 to 860 d with liveweight of 31–39 kg. ^{90}Sr and, ^{137}Cs were orally administered as a chloride; Ru as a nitrate.

(*continued on next page*)

Table 1 (*continued*)

Reference	Experimental details and data analysis
Pigs	
Annenkov et al. (1964b).	*Target radionuclide*: ^{90}Sr. *Target tissue*: bone. 34 piglets aged 75–90 days with 90–95 kg liveweight were orally administered ^{90}Sr for 30, 60, 90, 164 and 254 days into the dosing period and then 30 and 60 d after cessation of radionuclide chronic administration.
Astasheva et al. (1991).	*Target radionuclide*: ^{137}Cs. *Target tissue*: muscles. Clean feeding experiment with 25 pigs aged 18–20 m with liveweight of 65–70 kg. Half-life are not provided and these were calculated based on two component loss model (see "Data sources and data processing" section).
Buldakov (1968).	*Target radionuclide*: ^{239}Pu. *Target tissue*: bone. Eighteen piglets aged 75 d with liveweight of 10–12 kg were given a single intravenous administration of 1% Pu citrate (pH ≈ 6.5). Bones were sampled 1, 9, 65, 330, 640 d following Pu administration.
Burov and Sarapul'tsev (1974).	*Target radionuclide*: ^{106}Ru. *Target tissue*: bone, muscle, liver, kidney. 15 piglets aged 20 d with average liveweight of 3.4–4.0 kg were sampled 2, 4, 8, 16, 32 and 64 d after a single intravenous administration of Ru nitrate with a pH of c.1.5.
Ilyin and Moscalev (1961).	*Target radionuclides*: ^{32}P, ^{90}Sr, ^{137}Cs. *Target tissues*: muscle, heart, liver, kidney. 14 runner pigs aged 3.5 m (liveweight of 95–108 kg) orally administered ^{32}P, ^{90}Sr, ^{137}Cs for 85 d. Pigs were sampled 15, 29, 53 and 86 d into the dosing period and then 18, 30 and 60 d after cessation of administration.
Panchenko et al. (1974).	*Target radionuclide*: ^{90}Sr. *Target tissue*: muscle, bone. Summary of a large scale experiment with chronic oral administration of ^{90}Sr to 25 pigs aged at start of experiment from 150 d with liveweight 270–320 kg. ^{90}Sr was administrated as a chloride.
Shilov (1980).	*Target radionuclide*: ^{137}Cs. *Target tissue*: muscle, heart, lung, liver, kidney, spleen, blood, fat, bone. 24 piglets aged 5 d orally administered ^{137}Cs for 60 d (with live weigh on the time cessation 15–17 kg), were sampled on 1, 4, 8, 20, 60, 150 and 300 d following cessation of ^{137}CsCl administration (pH = 3). Half-lives are given for muscle and bone only It was possible to calculate further half-lives from data given.
Sirotkin et al. (1978).	*Target radionuclides*: ^{137}Cs *Target tissues*: liver. The paper provides a summary of a large number of studies with adult pigs aged 340–720 d with liveweight of 120–170 kg. Radionuclides were orally administered as a chloride.
Sirotkin (1987).	*Target radionuclide*: ^{137}Cs. *Target tissues*: muscle, liver, thyroid.
Wokken (1973).	*Target radionuclide*: ^{137}Cs. *Target tissue*: muscle, liver. Based on review of classified studies carried out in St. Petersburg by the author. Cited in details in Ilyin and Moscalev, 1961.
Rabbits	
Avrunina (1965).	*Target radionuclide*: ^{65}Zn. *Target tissue*: Whole body data for rabbits with liveweight of 3.2–3.8 kg.
Annenkov (1967)	*Target radionuclide: ^{90}Sr. Target tissue*: Muscles. The details of the experiment are not given.
Kurliandskaya (1957).	*Target radionuclide*: ^{137}Cs. *Target tissue*: bone. Rabbits with liveweight 4 kg.
Hens and geese	
Astasheva et al. (1992).	*Target radionuclide*: ^{137}Cs. *Target tissue*: blood, heart, kidney, liver, lung and muscle. Clean feeding experiment with 25 geese aged 3 y, with average liveweight 3.5 kg
Buldakov et al. (1959).	*Target radionuclide*: ^{90}Sr. *Target tissue*: muscle.
Koldaeyva and Sarapul'tsev (1968)	*Target radionuclide*: ^{90}Sr. *Target tissues*: muscles, bones 147 cocks aged 23 d, 60 d, 155 d were sampled 1, 2, 5, 10, 30, 100 and 200 d after a single oral administration of $SrCl_2$.
Koldaeyva et al. (1969).	*Target radionuclide*: ^{90}Sr. *Target tissue*: bone, eggs. 30 hens aged 8–9 m with liveweight 1.3–1.6 kg given a single oral administration of $^{90}SrCl_2$ and sampled 1, 16, 32, 64, 128 and 250 d following oral administration. 145 eggs were sampled over a period of 128 d following single oral administration of $^{90}SrCl_2$.
Koldaeyva and Sarapul'tsev (1972)	*Target radionuclide*: ^{137}Cs. *Target tissues*: bone, muscle, liver, heart, lung, spleen, kidney and eggs. 35 hens aged 12 m with average liveweight 2 kg given a single oral administration of ^{137}CsCl and sampled 1, 8, 16, 32, 64, 128 and 200 d after dosing.
Martyushov et al. (1984).	*Target radionuclide*: ^{238}U. *Target tissue*: muscle, liver, kidney and spleen. Experimental details were not specified. Half-lives are given as a range across muscle and other tissues without subdivision among individual tissues.
Nizamov (1973).	*Target radionuclide*: ^{131}I. *Target tissue*: Muscle, thyroid, blood, spleen, lung, kidney, liver, bone. 100 chicks aged 20 d exposed to ^{131}I for 30 d were slaughtered at 1, 8, 15, 22, 29, 36, 43, 50, 57 and 64 day after cessation of oral administration of ^{131}I. Although, redistribution of ^{131}I among different tissues is discussed, half-lives were given only for thyroid.
Panchenko et al. (1966).	*Target radionuclide*: ^{90}Sr. *Target tissue:* muscles, skeleton, eggs. 50 cocks aged 6 months with average liveweight 1.6 kg and 40 hens aged 20 months with average liveweight 1.8 kg were studied. Cocks were slaughtered (5 cocks per data point) over 5, 10, 15, 20, 30 and 35 days after start of chronic administration; hens were slaughtered on 5, 15, 30 and 35 d following cessation of 35 days administration. 187 eggs were measured sampled at the same dates.
Shilov and Koldayeva (1978)	*Target radionuclide*: ^{137}Cs. *Target tissues*: muscle, heart, lung, liver, kidney, spleen, stomach (muscles) and bone. 90 cocks aged 10–15 weeks with liveweight 0.8–1.1 kg were exposed to ^{137}Cs for 360 d. Five cocks were sampled 5, 8, 30, 65,150 and 360 d during oral administration and 5–6 cocks were sampled 1, 3, 8, 30, 60, 120 and 150 d after cessation of ^{137}Cs administration. Although data were suitable for half-life assessments, they were not given in the paper.
Sirotkin (1987).	*Target radionuclides*: ^{3}H, ^{54}Mn^{59}Fe and ^{65}Zn. *Target tissue*: eggs. Summary of experiments on chronic oral administration over 64 d to 96 adult hens. Eggs of 3 hens of 10 weeks age were studied for 360 days. Radionuclides were supplied as chlorides.

Such values can be particularly relevant when evaluating the effectiveness and practicality of management options that aim to reduce radionuclide activity concentrations in animal-derived foodstuffs (i.e. clean feeding, change of grazing regime, or use of feed additives).

Data on transfer parameter values for radionuclide transfer to farm animals were recently extensively reviewed (IAEA 2009; Fesenko et al., 2007b; Howard et al., 2009a,b). However, up to now there have been no comparable reviews of biological half-lives of radionuclides in farm animals. This paper presents a collation of $T^b_{1/2}$ values from the Russian language literature. The data have been compared with those published in the international literature and will provide an input to the review being prepared within the IAEA MODARIA programme (see http://www-ns.iaea.org/projects/modaria/default.asp?s=8&l%20=116).

2. Data sources and data processing

Time-dependent data on radionuclide activity concentrations in tissues or products (e.g. milk, eggs) are required to derive biological half-lives. Only data from papers which provided clear and sufficiently detailed descriptions of experiments were included in our evaluation. Data also had to be sufficient for statistical derivation of $T^b_{1/2}$.

Preference was given to original publications; data from reviews (Sirotkin, 1987, 1991; Annenkov, 1980) were used when original information was not available. Since the three major reviews cited above frequently contained data from classified documents that are not available, they were often the key source of novel information. In our compilation we only used data from experiments where biological effects were not observed. Reference sources and brief outlines of the experimental details for key experiments are given in Table 1.

Altogether 98 Russian language references were reviewed, of which 47 documents were identified which provided novel data; the remainder were rejected because they did not provide adequate information on experimental details or duplicated data presented in other publications. The majority of the reviewed references (>60%) were related to transfer to cattle tissues, most of the other sources referred to hens and pigs. In terms of radionuclides, ~31% of reviewed data were for ^{90}Sr, 34% for ^{137}Cs, 11% for ^{131}I and 24% for other radionuclides, including ^{3}H, ^{54}Mn, ^{65}Zn, ^{59}Fe, ^{140}Ba, as well as Ru, U and Pu isotopes. The dominance of data on ^{90}Sr and ^{137}Cs is due to the importance of these radionuclides in releases from the Kyshtym and Chernobyl accidents (Alexakhin et al., 2004).

Radionuclides concentrations in all animal tissues are interconnected through the circulation of blood. Thus, the loss of radionuclides from any tissue will be influenced, to some extent, by the activity concentrations in, and rates of loss from, other tissues especially for longer-term data, with $T^b_{1/2}$ in all tissues tending towards that of the main ‘storage’ tissue (Beresford et al., 1998a). Studies have to be of sufficient length, and have appropriate sampling strategies, such that the different components of loss in any given tissue can be estimated.

For the vast majority of the studies, radionuclides were orally administered, an exception was Pu, and in some studies Ru, for which intravenous administration was used in some early experiments. We acknowledge that there is the possibility that injected radionuclides may behave differently from ingested radionuclides within the animal (e.g. see Mayes et al., 1996) but have included these nevertheless.

For most of the data, the $T^b_{1/2}$ values given in this paper are those reported by the original authors. However, the publications where half-lives were reported were only used after evaluation of the approach used for assessments of the derived $T^b_{1/2}$ values. Most half-life values presented in the literature were reported as effective half-lives, which includes the physical decay of the radionuclide. These data were recalculated to biological half-lives using:

$$T^b_{1/2} = \frac{T^{rd}_{1/2}\cdot T^{eff}_{1/2}}{T^{rd}_{1/2} - T^{eff}_{1/2}},$$

where T^{rd} is the radionuclides physical half-life and $T^{eff}_{1/2}$ is the effective half-life. For single components of loss half-lives were estimated as the exponential equation fit, e.g.:

$$A(t) = A_0\cdot e^{-\frac{0.693\cdot t}{T^b_{1/2}}},$$

Where: *A₀* is the activity concentration at the end of chronic administration or in the case of single administration studies, the maximum observed radionuclide activity concentration (which was usually observed within one day after the administration); *A(t)* is the activity concentration of the radionuclide in tissue at time *t*.

The dynamics of loss from animal tissues is generally multicompartmental. For example, in a two component loss model:

$$A(t) = A_0\cdot\left(\alpha_1\cdot e^{-\frac{0.693\cdot t}{T^{b(1)}_{1/2}}} + (1-\alpha_1)\cdot e^{-\frac{0.693\cdot t}{T^{b(2)}_{1/2}}}\right),$$

where α_1 is the fraction of activity lost in the first component, $T^{b(1)}_{1/2}$ is the biological half-life reflecting fast loss and $T^{b(2)}_{1/2}$ is that reflecting the slow loss from a given tissue.

In some cases we had to calculate $T^b_{1/2}$ values by fitting the reported data to a two component loss model.

The STATISTICA software (release 8) has been used to process the data (http://www.statsoft.com/). The subsequent tables quote R^2 values where they are provided in the source reference or were calculated when fitting the data. The data reviewed are compared with those published in English language literature although a comprehensive review was not conducted.

The rates of uptake and loss of radionuclides varies between animals and tissues. For some radionuclides, such as radiocaesium, $T^b_{1/2}$ seems to be associated with the metabolic turnover rate (Sirotkin, 1987; Beresford and Vives I Batlle, 2013; Beresford and Wood, 2014). For others, it is controlled by stable element status. For instance, radiostrontium release from tissues is affected by changes in calcium metabolism including mobilisation of major body storage sites such as bone for during peak lactation in dairy animals (Sirotkin, 1987). Factors affecting biological half-lives are discussed below where relevant information is available from the source references.

3. Cattle

3.1. Milk

Data from 22 studies on radionuclide transfer to cow milk carried out between 1964 and 2008 were assessed to derive $T^b_{1/2}$ in milk. The studies included experiments using a single administration of radionuclides and six field studies where animals were removed from contaminated to uncontaminated areas (Table 2).

Data were available for 12 radionuclides: ^{45}Ca, ^{59}Fe, ^{89}Sr, ^{90}Sr, ^{95}Zr, ^{99}Mo, ^{106}Ru, ^{131}I, ^{132}Te, ^{137}Cs, ^{140}Ba, ^{144}Ce. Most of the $T^b_{1/2}$ values available for milk were for ^{131}I, reflecting the importance of radioiodine-milk exposure pathway for accidental situations. A single loss exponential model generally best fitted data from single administration studies with sampling typically over 12–14 d $T^b_{1/2}$ for a single exponential fit varied across all radionuclides within a narrow range of 1.0–2.7 d (Table 2). The shortest $T^b_{1/2}$ values were measured for ^{99}Mo, ^{131}I and ^{132}Te. $T^b_{1/2}$ derived for different radionuclides from these short-term studies are similar and a half-life of approximately 2 d describes the decrease of all radionuclides in cow milk after a single administration.

For data from some studies (Sirotkin et al., 1972a and Fedorov et al., 1973), a two or three exponential fit for ^{99}Mo and ^{131}I was found to be better than a single exponential fit. For ^{131}I, Sirotkin et al. (1972a) calculated a three exponential fit with $T^b_{1/2}$ of 0.6 d (0.68),[1] 1.2 day (0.37) and 15 d (0.013). These values can be explained by redistribution of radionuclides among animal tissues after single administration and, in particular, by a relatively slow uptake and release of ^{131}I by the thyroid gland. In a long term, chronic administration, study with ^{90}Sr, Sirotkin et al. (1970) recorded a four exponential fit with $T^b_{1/2}$*’s* for Sr in milk of 0.4–0.5 d (0.92–0.95), 2.5–3.5 d (0.048–0.077), 15.0–17.5 d (3.7×10^{-3}–4.0×10^{-3}) and 305–325 d (5.0×10^{-4}–7.0×10^{-4}), reflecting the dynamics of accumulation and excretion of ^{90}Sr from different tissues, and, in particular, from the bone (the slowest fraction) (Sirotkin, 1987). However, the fractions related to the long-term components were small compared with the fast component; the Sirotkin et al. (1969) study was 330 days long enabling the longer loss components to be identified.

As observed for the Russian language literature, other literature $T^b_{1/2}$ values for cow milk for a wide range of elements (Co, Cr, Cs, Sr, I, Ba, Mn, Mo, Nb, Fe, Te, Tc, and Zr) are all generally in the range 0.6–3.5 d (e.g. Voigt et al., 1989; Fabbri et al., 1994; Johnson et al., 1988; Van Bruwaene et al., 1984; Vandecasteele et al., 2000; Garner and Sansom, 1959). Biological half-lives of radionuclides in the milk of sheep and goats also tend to be within this range (e.g.

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[1] Numbers in parenthesis after $T^b_{1/2}$ values are the fraction of loss corresponding to that $T^b_{1/2}$.

Table 2
Biological half-lives of radionuclide activity concentrations in cow's milk. Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$; R^2 is reported where given in the source reference.

Nuclide	$T_{p,}$ h[a]	$A_{0,}$ %[b]	α_1	Biological half-lives (days)		R^2	Reference
				Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$		
Single administration							
^{45}Ca	24	0.52	1	1.6	–	0.99	Sirotkin and Sarapul'tsev (1973).
^{45}Ca		0.8	1	1.7	–		Korneyev et al. (1989).
^{89}Sr	60	0.032	1	2.2	–		Fedorov et al. (1973)
^{89}Sr	24–60	0.032	1	2.1	–		Prister (2008).
^{90}Sr		0.08	1	2.1	–	1.0	Sirotkin and Sarapul'tsev (1973).
^{90}Sr	24	0.11	1	2.1	–		Korneyev et al. (1989).
^{90}Sr			0.92–0.95	0.4–0.5	2.5–3.5		Sirotkin et al. (1969) [c]
^{95}Zr		0.0012	1	1.8	–	0.97	Sirotkin and Sarapul'tsev (1973).
^{99}Mo	24	0.09	0.95	1.1	2.5		Fedorov et al. (1973).
^{99}Mo	24	0.09	0.95	1.2	3.2		Prister (2008).
^{106}Ru		0.0043	1	2.1	–	0.90	Sirotkin and Sarapul'tsev (1973).
^{131}I	12	0.8	1	2.1	–		Korneyev and Sirotkin (1970) [d]
^{131}I	12		0.47	1.1	5.9		Fedorov et al. (1973).
^{131}I		1.2	1	1.0	–	0.96	Sirotkin and Sarapul'tsev (1973).
^{131}I[e]	6	1.47	0.99	0.7	13.8		Sirotkin et al. (1972a).
^{131}I[f]	20	0.8–1.15	0.68	0.6	1.2 (0.307)[g]		Sirotkin et al. (1972a).
^{59}Fe	48	0.1			–		Sirotkin et al. (1980).
^{132}Te	72		1	0.9	–		Fedorov et al. (1973).
^{137}Cs		0.48	1	1.7	–	0.95	Sirotkin and Sarapul'tsev (1973).
^{137}Cs	48	0.42	1	2.0	–	0.96	Korneyev et al. (1989).
^{140}Ba	24	0.005	0.66	1.0	9.4		Fedorov et al. (1973).
^{140}Ba		0.018	1	2.7	–	0.84	Sirotkin and Sarapul'tsev (1973).
^{144}Ce		0.0024	1	2.1	–	0.95	Sirotkin and Sarapul'tsev (1973).
Chronic administration							
^{90}Sr			0.8	3.0	96.0		Annenkov (1964a).
^{137}Cs			1	7.3	–		Kudryavtsev and Sirotkin (1991).

[a] Time to peak maximum concentration (hours).
[b] % of the injected amount at the time to peak maximum (*Tp).*
[c] A third and a fourth component were also fitted to the data, these were 15–17.5 d (3.7×10^{-3}–4.0×10^{-3}) and 305–325 d (5.0×10^{-4}–7.0×10^{-4}).
[d] Recalculated based on the data presented in the paper.
[e] Aqueous^{131}I.
[f] I-131 incorporated within feed.
[g] Fraction assigned to the second component; A third component of 15 d (0.013) was also fitted to the data.

Johnson et al., 1988; Howard et al., 1993; Lengemann and Wentworth, 1979; Hansen and Hove, 1991; Bosembriante et al., 1991). A notable exception is the observation of Johnson et al. (1988) who found longer $T_{1/2}^{b}$ values for Zr (5.2 d) and Nb (9.7 d) in goat milk than cow milk (1.6 d for Zr and 1.2 d for Nb). However, this study was conducted using only one cow and three goats.

3.2. Muscle

The data for muscle were derived from long-term experiments with chronic administration and in the case of one study, considering Cs, a short-term experiment following single administration (Table 3).

For ^{90}Sr in muscle, the fast first exponential loss $T_{1/2}^{b}$'s derived from experiments with cattle of different ages (from 60 days to 6 year) varied from 3.0 to 4.0 d (Table 3). The $T_{1/2}^{b}$ for the slower second exponential loss ranged from 180 to 700 d. The values of $T_{1/2}^{b(2)}$ derived from the Russian language publications are all longer than the value of 100 d used for food chain modelling by Müller and Pröhl (1993) for the meat of all ruminants including cattle. However, whereas the Russian language literature has from 10 to <60% of loss occurring in this long component, Müller and Pröhl (1993) suggest 80%.

From the seven papers summarized in Table 3, the fast $T_{1/2}^{b}$ for ^{137}Cs derived for cattle muscle ranged from 3 to 22 d. There was a tendency for larger components of loss (i.e. α_1) associated with the longer $T_{1/2}^{b(1)}$ estimates.

The $T_{1/2}^{b(2)}$ values for Cs varied from 46 to 84 d Voigt et al. (1989) reported a single $T_{1/2}^{b}$ of 20–30 d for the muscle of adult cows following chronic administration of ^{137}Cs contaminated feed. Voigt et al.'s values are broadly in agreement with those in Table 3 which are all double exponential fits. Voigt et al. (1989) also presents $T_{1/2}^{b}$ for young cows that ranged from 50 to 60 d; this range is similar to the slow $T_{1/2}^{b}$ for heifers (young female cows before their first calving) given by Astasheva et al. (1991). A $T_{1/2}^{b}$ for beef bulls of 30–40 d was also presented by Voigt et al. (1989) which are also similar to the slow $T_{1/2}^{b}$ estimated by Astasheva et al. (1991) for bulls aged 10–20 months (Table 3). Following a single oral administration of ^{137}Cs, Twardock and Crackel (1969) reported three phases of loss for the whole body of adult cattle with $T_{1/2}^{b}$'s of 0.6 (22%), 4.3 (41%) and 33 (37%) d, respectively. The latter two phases are similar to the $T_{1/2}^{b}$ in muscle reported by Sirotkin (1987) in Table 3 of 3.0 d and 46.2 d respectively (and also some of those values for muscle following chronic administration presented in Table 3).

The data for muscle given in Table 3 for both ^{90}Sr and ^{137}Cs show no age dependency in apparent agreement with the Voigt et al. data (1989). In contrast, Twardock and Crackel (1969) reported that the rate of loss following single administration of ^{137}Cs was faster in two 3 month old calves than in three adult (non-lactating) cattle. Average $T_{1/2}^{b}$ for three exponential phases in the calves were 0.9 d, 4.1 d and 24.4 d respectively, with a higher fraction (0.33) of the loss in the fast component compared with that (0.22) for adult cattle (0.7 d, 4.7 d and 37.4 d respectively).

Within Table 3 a single $T^{b}_{1/2}$ for ^{131}I of 7 d was reported by Sirotkin (1987) for cattle muscle. Although Digregorio et al. (1978), gives a $T^{b}_{1/2}$ for ^{131}I of 8.1 d for whole-body of cattle, this cannot be confirmed from the cited paper (Lengemann & Comar 1964) and appears to be misquoted being the physical half-life of ^{131}I (which is cited as 8.1 d by Lengemann & Comar).

3.3. *Other tissues*

Data for $T^{b}_{1/2}$ in most other cattle tissues were best described using a two-component loss model. These are summarized for studies with both single and chronic administration of radionuclides in Tables 4 and 5. Data for various tissues of cattle from experiments with a single administration are available for ^{45}Ca, ^{90}Sr, ^{131}I and ^{137}Cs. Whereas the studies of Sirotkin et al. (1972a), Sirotkin (1987) using ^{137}Cs and ^{131}I had a one year duration, those considering ^{45}Ca and ^{90}Sr (Korneyev et al., 1989) were much shorter, lasting for only 9–16 d Korneyev et al. (1989) only reported data for blood (and excreta – presented in Table 4 for completeness but not discussed here) for which only single components of loss were observed for both Ca and Sr. If the study had been conducted for a longer period then it would be expected that a longer-term loss component would be observed for these radionuclides which are deposited in bone.

For all radionuclides, loss from bone was best described by a single exponential model. The longest half-lives in bone were for Sr with values of 600–700 d and 3011 d being estimated by Panchenko et al. (1974) and Sirotkin (1987) respectively. In the case of the Panchenko et al. data, the half-life value was similar to the $T^{b(2)}_{1/2}$ for muscle measured within the same study (Table 3); Sirotkin (1987) did not measure $T^{b}_{1/2}$ for muscle. Sirotkin et al. (1972b), 1978) reported $T^{b}_{1/2}$ values for bone of 84 d and 284 d for ^{137}Cs and ^{144}Ce, respectively.

In Table 4 for single administration, both fast and slow $T^{b}_{1/2}$ values, as well as fractions of the fast loss components assessed for same tissues can be seen to be relatively similar for ^{45}Ca, ^{90}Sr and ^{137}Cs. Relatively long biological half-lives for ^{131}I were measured in thyroid (10.7–29 d) (Table 4); the thyroid is known to take up iodine from the blood rapidly (Sirotkin et al., 1972a; Sirotkin, 1987; Beresford et al., 1997). The ^{131}I $T^{b}_{1/2}$ in blood was longer than that of milk in the study of Sirotkin et al. (1972a); this may be to the presence of organically bounded iodine in blood which does not readily transfer to milk (Crout et al., 2000). For single administration studies, the $T^{b}_{1/2}$ for ^{131}I in blood (5.7 d) was longer than the range of $T^{b}_{1/2}$ of other radionuclides (^{45}Ca, ^{90}Sr and ^{137}Cs) in blood (0.9–2.2 d). A longer $T^{b}_{1/2}$ was observed for ^{137}Cs in blood after chronic administration (Table 4).

Data for chronic administration in Table 4 are largely for ^{137}Cs. If models derived from single administration studies were used to make predictions, these would give similar predictions to those parameterised using data derived from chronic administration studies in the first few weeks. In the longer term the models using the chronic administration data would predict slower rates of loss.

3.3.1. *Comprehensive experiment with single administration of simulated "fresh" fission products*

Information on accumulation, redistribution and excretion of fission products with a composition reflecting that expected about 10 days after a nuclear weapons explosion (termed "fresh" by the authors) were presented by Fedorov et al. (1973). These experiments were performed at the beginning of the 1970's at a research station located at the "Mayak" radiochemical plant. The purposes were: (i) to simulate radionuclide transfer to animals in the case of short-term accidental deposition or use of nuclear weapons; (ii) to validate dosimetric models; and (iii) to assess biological effects on animals due to ingestion of radionuclides. Recently, this experiment was described in Prister (2008) who reported some additional information.

The radionuclide mixture was sprayed onto harvested grass as a nitrate solution which was then well mixed before being fed to five groups of cows. The administered radionuclide activities ranged from relatively 'low' up (6.3×10^{10} Bq) to 'rather high' (1.1×10^{12} Bq), which resulted in radiation sickness and death of the cows receiving the highest activities. To avoid effects of radiation on metabolism of radionuclides, only data for animals with the lowest doses, for which effects were not observed, were used to assess the biological half-lives.

Table 3
Biological half-lives of radionuclide activity concentrations in muscles of cattle. Where only one component of loss was fitted this is presented under $T^{b(1)}_{1/2}$; R^2 is reported where given in the source reference.

Nuclide	α_1	Biological half-lives (days)		R^2	Reference
		Fast loss, $T^{b(1)}_{1/2}$	Slow loss, $T^{b(2)}_{1/2}$		
^{90}Sr	0.42	3.5	200		Annenkov (1969).
^{90}Sr	0.90	3.0–4.0	600–700		Panchenko et al. (1974).
^{90}Sr	0.60[a]	3.5	270	0.62	Sirotkin et al. (1976).
^{90}Sr	0.42[b]	3.7	180	0.86	Sirotkin et al. (1976).
^{131}I	1.0	7.0			Sirotkin (1987).
^{137}Cs	0.37	3.7	70.0		Sirotkin (1987).
^{137}Cs	0.51	6.5	46.0		Sirotkin et al. (1972b)[3]
^{137}Cs	0.45	3.0	46.2		Sirotkin (1987).
^{137}Cs	0.70	22.3	81.0	0.89	Iliazov (2001).
^{137}Cs	0.84[a]	15.4	63.0	0.97	Sirotkin et al. (1976).
^{137}Cs	0.93[b]	6.7	84.0	0.90	Sirotkin et al. (1976).
^{137}Cs	0.35	3.0	55.0	0.96	Sirotkin et al. (1976).
^{137}Cs	0.45	11.1	36.3		Astasheva et al. (1991) [c]
^{137}Cs	0.65	7.3	43.1		Astasheva et al. (1991) [d]
^{137}Cs	0.64	8.0	46.0		Astasheva et al. (1991) [e]
^{137}Cs	0.61	8.3	38.3		Iliazov (2001).

[a] Calves were receiving ^{90}Sr and ^{137}Cs for 150 d (group 2), see Table 1.

[b] Calves were receiving ^{90}Sr and ^{137}Cs for 300 d (group 3), see Table 1.

[c] Bulls.

[d] Cows.

[e] Heifers (young females).

Table 4
Biological half-lives of radionuclide activity concentrations in different tissues (other than muscle) and excreta of cattle. Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$; R^2 is reported where given in the source reference.

Nuclide	Tissue	α_1	Biological half-lives (days)		Reference
			Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$	
Single administration					
^{45}Ca	Blood	1.0	1.7	–	Korneyev et al. (1989).
^{45}Ca	Faeces	0.97	0.73	2.2	Korneyev et al. (1989).
^{45}Ca	Urine	1.0	2.2	–	Korneyev et al. (1989).
^{90}Sr	Blood	1.0	2.2	–	Korneyev et al. (1989).
^{90}Sr	Skeleton	1.0	600–700		Panchenko et al. (1974).
^{90}Sr	Skeleton	1.0	3011		Sirotkin (1987).
^{90}Sr	Faeces	0.96	0.69	1.7	Korneyev et al. (1989).
^{90}Sr	Urine	1.0	1.9	–	Korneyev et al. (1989).
^{131}I	Blood	1.0	5.7		Sirotkin et al. (1972a).
^{131}I	Liver	1.0	6.8		Sirotkin (1987).
^{131}I	Thyroid	1.0	24.3[a]	–	Sirotkin et al. (1972a).
^{131}I	Thyroid	1.0	10.7[b]	–	Sirotkin et al. (1972a).
^{131}I	Thyroid	1.0	15–24	–	Sirotkin (1987).
^{137}Cs[a]	Blood	0.83	0.9	69.3	Sirotkin (1987).
^{137}Cs	Heart	0.91	6.5	56.0	Sirotkin (1987).
^{137}Cs	Kidney	0.95	5.6	24.3	Sirotkin (1987).
^{137}Cs	Liver	0.89	6.5	33.0	Sirotkin (1987).
^{137}Cs	Lung	0.89	5.1	33.0	Sirotkin (1987).
^{137}Cs	Skin	0.71	2.4	23.3	Sirotkin (1987).
^{137}Cs	Spleen	0.87	6.2	31.7	Sirotkin (1987).
Following chronic administration					
^{90}Sr	Liver	0.43	3.5	178	Sirotkin (1987).
^{137}Cs	Offal	0.78	3.7	74.0	Sirotkin et al. (1972b)
^{137}Cs	Skin	0.74	5.9	106	Sirotkin et al. (1972b)
^{137}Cs	Blood	0.75	4.1	145	Sirotkin et al. (1972b)
^{137}Cs	Skeleton	1	84		Sirotkin et al. (1972b)
^{137}Cs	Skeleton	0.91	1.1	300	Sirotkin et al. (1978).
^{137}Cs	Liver	0.79	2.9	110	Sirotkin et al. (1978).
^{144}Ce	Skeleton	1	284		Sirotkin et al. (1978).

[a] For consumption of aqueous ^{131}I.
[b] For consumption of ^{131}I incorporated within feed.

The advantage of this study is that information was provided for a large number of radionuclides, the activity concentrations of radionuclides were measured under the same conditions and the data were processed and interpreted using the same approach. Furthermore, biological half-life values were derived for different animal compartments and radionuclides within a single experiment. Conversely, the drawback of the study was its short duration with animals being slaughtered from 12 h to 12 days after radionuclide administration and the short physical lives of some of the radionuclides used (^{132}Te and ^{99}Mo < 80 h). Examples of data for some radionuclides derived from the study are shown in Fig. 1; parameters of loss for all radionuclides in animal tissues are given in Table 5.

Most of the losses could be described by single exponentials, but a few radionuclide-tissue combinations had a double exponential fit, notably for ^{131}I and for blood for a total of three isotopes. In part, the lack of multiple component fits to the data will have been due to the short physical half-lives of the radionuclides studied.

High ^{131}I activity concentrations in blood were observed peaking at 3 h after radionuclide administration, demonstrating the rapid and high iodine absorption rate in the gastrointestinal tract (Fesenko et al., 2007a; Howard et al., 2009c). The highest ^{131}I activity concentrations (five–six orders of magnitude higher than in other tissues were again found in the thyroid; those in the liver and kidney were similar to each other and approximately 10 fold higher than that of muscle. The peak ^{131}I activity concentration in the kidney was reached at 3 d, later than that for other tissues. Except for the thyroid, excretion rates of ^{131}I from animal tissues were rapid. The main excretion pathway for ^{131}I was via the kidney; nearly 30% of administrated ^{131}I was lost in urine. The biological half-lives estimated by Fedorov et al. (1973) for ^{131}I in milk are similar to the other values estimated from the Russian language literature (see Table 2) and are compared to wider literature below.

Peak activity concentrations of ^{99}Mo in blood were observed 6 h after administration. The highest activity concentrations were in liver, followed by kidney, blood and, finally, muscle, where activity concentrations of ^{99}Mo were about 100 fold lower than those in liver and kidney (Table 5). The most important accumulating organ, liver, took up a maximum of 8.4% of the administered ^{99}Mo.

Coughtrey and Thorne (1983) refer to the study of Anke et al. (1971) in which goats were orally administered ^{99}Mo with the highest concentrations being observed in liver, in agreement with Fedorov et al. (1973); The biological half-lives reported by Fedorov et al. (1973) for soft tissues are within the range of 1–10 d as suggested by Reichle et al. (1970) for (primarily homoeothermic) vertebrates.

The absorption of ^{132}Te (as inferred from the maximum percentages observed in tissues) was lower than that of ^{131}I and ^{99}Mo. Although the distribution of ^{132}Te among tissues was similar to that of ^{99}Mo, the normalised ^{132}Te peak activity concentrations were two orders of magnitude lower. Reichle et al. (1970) places Te within a 10–100 d $T_{1/2}^{b}$ category which is longer than the values reported by Fedorov et al. (1973) for soft tissues (Table 5). Mullen et al. (1974) present data for calves slaughtered 3, 9 and 21 days after a single oral administration of $^{129\mathrm{m}}$Te. Whilst $T_{1/2}^{b}$ values cannot be calculated from these data, the retention of Te appears to be much longer than that observed by Fedorov et al. (1973) ($T_{1/2}^{b} = 0.6–1.8$ d). Mullen et al. (1974) observed no decrease in

Table 5
Biological half-lives of simulated ‘fresh fission product’ radionuclide activity concentrations in tissues of dairy cows. Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$; (Fedorov et al., 1973; Prister, 2008).

Nuclide	T_p, hours[a]	A_0, %[b]	α_1	Biological half-lives (days)	
				Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$
^{89}Sr					
Liver	48	$(4.3 \pm 1.3) \times 10^{-4}$	1.0	2.3	–
Kidney	12	$(4.9 \pm 1.6) \times 10^{-3}$	0.6	0.3	3.3
Muscles	48	$(5.5 \pm 1.8) \times 10^{-4}$	1.0	2.2	–
Blood	36	$(8.6 \pm 2.7) \times 10^{-3}$	0.6	1.0	2.6
Skeleton	70–290	$(4.0 \pm 1.0) \times 10^{-2}$	–	–	–
^{99}Mo					
Liver	36	$(9.4 \pm 1.7) \times 10^{-1}$	1.0	4.5	–
Kidney	48	$(7.2 \pm 3.0) \times 10^{-1}$	1.0	2.5	–
Muscle	24	$(3.0 \pm 1.0) \times 10^{-3}$	1.0	3.5	–
Blood	6	$(3.7 \pm 1.1) \times 10^{-3}$	0.81	0.3	1.8
^{131}I					
Thyroid	12	$(1.2 \pm 0.3) \times 10^{4}$	1.0	63.0	–
Liver	12	$(3.1 \pm 1.0) \times 10^{-1}$	0.76	1.5	8.0
Kidney	72	$(3.5 \pm 1.0) \times 10^{-1}$	1.0	2.2	–
Muscle	12	$(4.4 \pm 0.5) \times 10^{-2}$	0.47	1.7	9.0
Blood	3	$(2.3 \pm 0.8) \times 10^{-1}$	0.35	1.7	3.9
^{132}Te					
Liver	24	$(4.7 \pm 1.5) \times 10^{-1}$	1.0	0.6	
Kidney	120	$(1.4 \pm 0.4) \times 10^{-1}$	1.0	1.6	
Muscle	72	$(8.4 \pm 1.0) \times 10^{-3}$	1.0	1.8	
Blood	48	$(5.0 \pm 1.6) \times 10^{-3}$	1.0	0.9	
^{140}Ba					
Liver	96	$(1.3 \pm 0.3) \times 10^{-3}$	1.0	13.0	–
Kidney	24	$(4.6 \pm 1.3) \times 10^{-3}$	1.0	0.7	–
Muscle	48	$(3.8 \pm 0.3) \times 10^{-4}$	1.0	2.0	–
Blood	24	$(3.7 \pm 1.2) \times 10^{-3}$	1.0	1.6	–
Skeleton	72	$(6.3 \pm 2.7) \times 10^{-2}$	1.0	12.0	–

[a] Time to peak maximum concentration (hours).
[b] % of the administered activity at time T_p.

the activity concentration of ^{129m}Te in muscle, kidney or liver over 21 d.

In contrast to other radionuclides, for ^{89}Sr and ^{140}Ba the highest activity concentrations were in the bone and the lowest in liver and muscle. The shortest biological half-lives were from kidney (0.3–0.7 d, see Table 5)).

4. Sheep and goats

$T_{1/2}^{b}$ values measured for sheep and goats are given in Tables 6 and 7. The data were largely for ^{137}Cs. However, some information was also given for ^{65}Zn, ^{90}Sr, ^{106}Ru and ^{144}Ce. Most of the data were best fitted by a double exponential model, although for ^{144}Ce a single exponential model was used for all tissues.

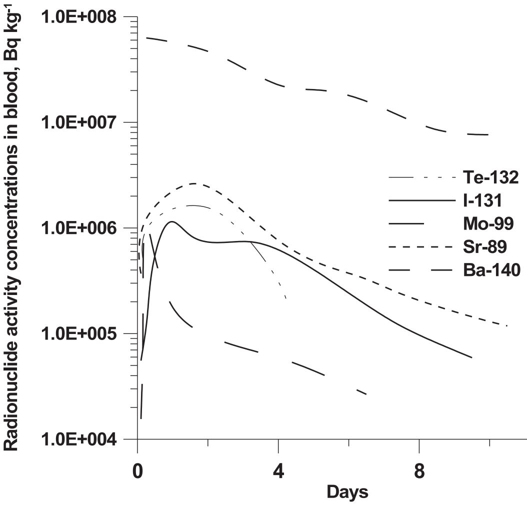

Fig. 1. Variation with time in radionuclide activity concentrations in the blood of dairy cows. The data were normalised to administration of 1 Ci (3.7×10^{10} Bq) of each radionuclide.

The ^{90}Sr $T_{1/2}^{b}$ values in muscle ranged from 3 to 23.5 d (fast loss) and 40–300 d (slow loss), with the higher values associated with older (and larger) sheep (Table 6). The slow $T_{1/2}^{b}$ identified by Panchenko et al. (1974) for muscle was similar to that he calculated for bone (Table 7). For ^{90}Sr in bone, a relatively slow $T_{1/2}^{b(1)}$ (23.5 d) and relatively fast $T_{1/2}^{b(2)}$ (40 d) were calculated for 3 year old sheep by Buldakov (1961) (Table 6). For ^{137}Cs, the $T_{1/2}^{b(1)}$ values for muscle were about 10 d (α_1 ranged 0.70–0.76) (Buldakov, 1961, 1964; Sirotkin et al., 1978), whilst the $T_{1/2}^{b(2)}$ values varied from 38 to 68 d (Table 6). Half-life values as measured by Sirotkin (1987) were 3.0 d for the fast component (0.45) with a $T_{1/2}^{b(2)}$ of 46.2 d. Given the comparatively low fraction lost during the fast component as calculated by Sirotkin et al. (1978) the application of equations derived from the Sirotkin (1987) and Buldakov (1961, 1964) studies results in similar predictions for at least 100–200 days after ceasing feeding animals with contaminated feeds.

There is a considerable amount of data in the international literature on the biological half-life of Cs in sheep. Daburon et al. (1992) presented $T_{1/2}^{b}$ values for sheep of different ages and stages of reproductive cycle following chronic oral administration determined using live-monitoring. Daburon found increasing $T_{1/2}^{b(2)}$ values with age ranging from 14.1d for 50–65 day old lambs to c. 27d for adult ewes. The $T_{1/2}^{b(1)}$ ranged from 0.8 to 2.6 d with no age dependence. Daburon et al. (1991) found no difference in $T_{1/2}^{b}$ values between non-lactating sheep and lactating sheep

Table 6
Biological half-lives of radionuclide activity concentrations in muscle of sheep and goats. Where only one component of loss was fitted this is presented under.$T_{1/2}^{b(1)}$

Nuclide	α_1	Biological half-lives (days)		Reference
		Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$	
Sheep				
^{90}Sr	0.21	23.5	40.0	Buldakov (1961).
^{90}Sr	0.9	3–4	300	Panchenko et al. (1974).
^{137}Cs	0.75	9.3	37.7	Buldakov (1961).
^{137}Cs	0.7	10.4	68.0	Sirotkin et al. (1978).
^{137}Cs[a]	0.31	27	53.0	Buldakov (1964).
^{137}Cs	0.76	9.5	67.0	Buldakov (1964).
^{137}Cs	0.45	3.0	46.2	Sirotkin (1987).
Goat				
^{137}Cs	1.0	31		Sirotkin et al. (1978).

[a] Lambs obtained from contaminated sheep (see Table 1).

($T_{1/2}^{b(1)}$= 1.5–2 d; $T_{1/2}^{b(2)}$ c. 30 d). Beresford et al. (1998b) reported a range in $T_{1/2}^{b}$ values of 5–19 d for adult female sheep acknowledging that these $T_{1/2}^{b}$ values are more similar to those previously determined for lambs (e.g. 10 d (Howard et al., 1987)) than adult sheep (Crout et al., 1996; Coughtrey, 1990; Daburon et al., 1991, 1992; Voigt et al., 1989). However, Galer et al. (1993) reported a $T_{1/2}^{b}$ value of 12 d for adult sheep of a similar mass to those studied by Beresford et al. (1998a).

Data on $T_{1/2}^{b}$ in muscle of goats are rather limited in the Russian literature and available only for ^{137}Cs. Overall, the $T_{1/2}^{b}$ for ^{137}Cs in goat muscle reported by Sirotkin et al. (1978) for goats are consistent with those for sheep in the Russian (see Table 6) and international (see above) literature.

Table 7 provides information for sheep and goat tissues other than muscle from the Russian language literature. In agreement with the observations above for cattle, the longest $T_{1/2}^{b}$ (300 d) was for ^{90}Sr in bone (Panchenko et al., 1974)). The ^{137}Cs data on $T_{1/2}^{b}$ in sheep tissues originated from two experiments with adults (Buldakov, 1964) and 80–90 d old lambs (Sirotkin, 1987). The $T_{1/2}^{b}$ for ^{137}Cs estimated for some tissues (lung, liver) by Buldakov (1964) tended to be three-six fold longer than those estimated for lambs by Sirotkin (1987). A difference between the studies was that older animals (3 years and above) were used by Buldakov (1964) whereas Sirotkin (1987) studied young lambs. The young animals studied by Sirotkin (1987) would have been expected to have higher turnover rates than the adults studied by Buldakov (1964). The data of Buldakov (1964) for liver and lung have longer $T_{1/2}^{b(2)}$ estimates than those for muscle, though the second component of loss for these two tissues comprises less of the total Cs lost than it does for muscle (Tables 6 and 7).

Data for ^{144}Ce for sheep are also available from the Russian language studies. These data gave comparatively long $T_{1/2}^{b}$ values for bone of 118–960 d and for liver of 62.5–142 d, depending on age of the animals. Beresford et al. (1998a) presented $T_{1/2}^{b}$ values for cerium in a number of sheep tissues estimating two component $T_{1/2}^{b}$ values of 69 d (0.4) and 1350 d (0.6) for muscle and 88 d (0.44) and 1900 d (0.56) for liver. For kidney and bone single $T_{1/2}^{b}$ values of 380 d and 2050 d respectively were derived by Beresford

Table 7
Biological half-lives of radionuclide activity concentrations in tissues of sheep (other than muscle). Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$.

Nuclide	Tissue	α_1	Biological half-lives (days)		Reference
			Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$	
Sheep					
^{65}Zn	Blood	0.73	0.17	20.0	Abramova et al. (1984).
^{90}Sr	Skeleton	1.0	300		Panchenko et al. (1974).
^{137}Cs	Blood	0.83	0.9	69	Sirotkin (1987).
^{137}Cs	Lung	0.95	6.2	119	Buldakov (1964).
^{137}Cs	Lung	0.89	5.1	33.0	Sirotkin (1987).
^{137}Cs	Heart	0.91	6.5	56.0	Sirotkin (1987).
^{137}Cs	Kidney	0.92	3.7	28.0	Buldakov (1964).
^{137}Cs	Kidney	0.95	5.6	24	Sirotkin (1987).
^{137}Cs	Skin	0.71	2.4	23	Sirotkin (1987).
^{137}Cs	Skin	0.55	12.0	34	Buldakov (1964).
^{137}Cs	Spleen	0.87	6.2	32	Sirotkin (1987).
^{137}Cs	Offal	0.7	10.4	68.0	Buldakov (1964).
^{137}Cs	Liver	0.89	6.5	33.0	Sirotkin (1987).
^{137}Cs	Liver	0.82	11.4	204	Buldakov (1964).
^{137}Cs	Liver	0.95	4.7	267	Buldakov (1964).
^{144}Ce	Skeleton	1.0	118.0[a]		Buldakov and Burov (1967).
^{144}Ce	Skeleton	1.0	219.0[b]		Buldakov and Burov (1967).
^{144}Ce	Skeleton	1.0	960.0[c]		Buldakov and Burov (1967).
^{144}Ce	Lung	1.0	48		Buldakov (1961).
^{144}Ce	Liver	1.0	95.0	–	Sirotkin et al. (1978).
^{144}Ce	Liver	1.0	62.5[a]	–	Buldakov and Burov (1967).
^{144}Ce	Liver	1.0	94.5[b]	–	Buldakov and Burov (1967).
^{144}Ce	Liver	1.0	142.0[c]	–	Buldakov and Burov (1967).
Goat					
^{90}Sr	Bone	1.0	112	–	Panchenko et al. (1974).
^{106}Ru	Bone	0.3	10.7	38.5	Sirotkin et al. (1978).
^{137}Cs	Bone	0.83	3.8	52.9	Buldakov (1961).

[a] Lambs born from contaminated sheep (see Table 1).
[b] Lambs aged 20–25 d at the time of radionuclides administration.
[c] Ewes aged 80–200 d at the time of radionuclides administration.

et al. (1998a). The first component $T_{1/2}^{b}$ value estimated by Beresford et al. (1998a) for liver is similar to all the single compartment $T_{1/2}^{b}$ values shown in Table 7. Hence overall the Russian language data predict a more rapid excretion than the Beresford et al. data. The $T_{1/2}^{b}$ value in Table 7 estimated for bone appears to be considerably shorter than that given by Beresford et al. (1998a). However, Beresford et al. (1998a) found no significant reduction in the Ce activity concentration of bone over a 1 year following a single oral administration. Therefore the estimated $T_{1/2}^{b}$ will have a high uncertainty and is not different to the value in Table 7.

5. Pigs

Only 10 literature sources were identified to derive $T_{1/2}^{b}$ for pigs. In total, they provide information on five radionuclides, namely, ^{32}P, ^{90}Sr, ^{106}Ru, ^{137}Cs and ^{239}Pu (Table 8).

The $T_{1/2}^{b}$ values for ^{32}P calculated by Ilyin and Moscalev (1961) were similar for different tissues, varying from 9.3 d (kidney) to 26.7 d (muscle). It was not possible to estimate $T_{1/2}^{b}$ of P in bone as no loss was seen other than physical decay (physical half-life *c.* 14 d). Approximately 85% of body P is found in bone where it is present in hydroxyapatite crystals in contrast to phosphate esters in soft tissues (Favus et al., 2006). Given its role in bone development it is unsurprising that a long $T_{1/2}^{b}$ was estimated for this tissue, as was observed above for Ca and Sr; P retention and loss in bone varies depending upon physiological status (e.g. lactation, growth, pregnancy etc.) (Favus et al., 2006).

Sr-90 $T_{1/2}^{b}$ in bones ranged 112–500 d, depending on the age of the animal. The longest $T_{1/2}^{b}$ in bone (400–500 d) was observed by Panchenko et al. (1974) for 2–3 year old pigs. The shortest (112 d) determined by Annenkov et al. (1964b) was for pigs that were less than 1 year old. Panchenko et al. (1974) used a two component model to describe ^{90}Sr loss from muscle with the $T_{1/2}^{b(2)}$ (450 d, 0.1) being similar to that calculated for bones (Table 8). There is little English language data presenting Sr $T_{1/2}^{b}$ values for pigs. The review of Digregorio et al. (1978) contains a summary of the whole body $T_{1/2}^{b}$ values of Anderson and Crackel (1969) for ^{85}Sr in infant wild boar; these are broadly in agreement with data in Table 8.

For ^{137}Cs, the single component $T_{1/2}^{b}$ values for muscle of c. 16 d estimated from data presented by Ilyin and Moscalev (1961) was similar to the short component of loss estimated by Shilov (1980) which represented 99% of the initial Cs in muscle. In contrast, the data of Sirotkin (1987) and Astasheva et al. (1991) show relatively rapid $T_{1/2}^{b(1)}$ values (<4 d) representing c. 60% of total loss with longer $T_{1/2}^{b}$ values of 29–63 days representing the remaining 40%.

Ekman (1961) presents a number of slow compartment $T_{1/2}^{b}$ values for various tissues of pigs ranging between 21 and 30 d

Table 8

Biological half-lives of radionuclide activity concentrations in tissues of pigs. Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$. Half-lives calculated based on the data presented in the reviewed papers are given in *Italics*.

Nuclide	Tissue	α_1	Biological half-lives		R^2	Reference
			Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$		
^{32}P	Heart	1.0	13.8	–		Ilyin and Moscalev (1961).
^{32}P	Kidney	1.0	9.3	–		Ilyin and Moscalev (1961).
^{32}P	Liver	1.0	10.5	–		Ilyin and Moscalev (1961).
^{32}P	Muscle	1.0	26.7	–		Ilyin and Moscalev (1961).
^{90}Sr	Skeleton	1.0	400–500	–		Panchenko et al. (1974).
^{90}Sr	Skeleton	1.0	173–224	–		Ilyin and Moscalev (1961).
^{90}Sr	Skeleton	1.0	88[a] ± 26[b]	–		Annenkov et al. (1964b).
^{90}Sr	Skeleton	1.0	112[c] ± 26[b]	–		Annenkov et al. (1964b).
^{90}Sr	Muscle	0.9	4–5	450		Panchenko et al. (1974).
^{106}Ru	Skeleton	0.3	10.7	38.5	0.96	Burov & Sarapul'tsev (1974).
^{106}Ru	Kidney	0.59	4.5	17.7	0.98	Burov & Sarapul'tsev (1974).
^{106}Ru	Liver	0.70	2.9	23.9	0.98	Burov & Sarapul'tsev (1974).
^{106}Ru	Muscle	0.66	1.5	27.3	0.99	Burov & Sarapul'tsev (1974).
^{106}Ru	Skin	0.46	3.5	65.0	0.96	Burov & Sarapul'tsev (1974).
^{137}Cs	Skeleton	0.99	5.1	231		Shilov (1980).
^{137}Cs	Heart	1.0	15.3	–		Ilyin and Moscalev (1961).
^{137}Cs	Liver	0.10	15.5			Sirotkin et al. (1978).
^{137}Cs	Liver	0.79	2.9	110		Sirotkin et al. (1978).
^{137}Cs	Liver	1.0	15.5	–		Wokken (1973).
^{137}Cs	Muscle	0.63	2.5	63.0		Sirotkin (1987).
^{137}Cs	Muscle	0.99	15.8	330		Shilov (1980).
^{137}Cs	Muscle	1.0	15.9	–		Ilyin and Moscalev (1961).
^{137}Cs	*Muscle*	*0.56*	*3.4*	*28.6*	*0.97*	Astasheva et al. *(1991)*
^{137}Cs	*Heart*	*0.6*	*5.1*	*33.4*	*0.99*	Astasheva et al. *(1991)*
^{137}Cs	*Lung*	*0.4*	*4.9*	*27.8*	*0.99*	Astasheva et al. *(1991)*
^{137}Cs	*Liver*	*0.5*	*3.4*	*29.6*	*0.99*	Astasheva et al. *(1991)*
^{137}Cs	*Kidney*	*0.78*	*8.5*	*56.7*	*0.98*	Astasheva et al. *(1991)*
^{137}Cs	*Spleen*	*0.4*	*2.3*	*26.6*	*0.99*	Astasheva et al. *(1991)*
^{137}Cs	*Fat*	*1.0*	*29.4*	-	*0.98*	Astasheva et al. *(1991)*
^{137}Cs	*Blood*	*1.0*	*19.8*	-	*0.97*	Astasheva et al. *(1991)*
^{239}Pu	Skeleton	0.6	200	1200		Buldakov (1968).
^{239}Pu	Lung	1.0	85.0	–		Buldakov (1968).
^{239}Pu	Muscle	1.0	70.0	–		Buldakov (1968).

[a] Calculuted for feeding with contaminated feeds period.

[b] SD.

[c] Calculuted for decontamination period.

which are similar to the values estimated from Astasheva et al. (1991). Di Gregorio et al. (1978) summarises the data of Twardock and Crackel (1969) for the whole body of adult wild boar and present a $T_{1/2}^{b(1)}$ value of c. 3.5 d (18%) and second component of c. 35 d (72%) again in agreement with Astasheva et al. (1991).

There are relatively few data on Pu turnover in domestic animals. Coughtrey (1990) quotes a study by Buldakov et al. (1970) citing a $T_{1/2}^{b}$ value of 5100 d for Pu in the liver of pigs. For all farm animals Coughtrey (1990) recommends a $T_{1/2}^{b}$ for bone of 50 years and 20 years for soft tissues. Comparatively, the $T_{1/2}^{b}$ values presented for pigs in Table 8 appear relatively short. However, the study of Buldakov (1968) was only 640 d which was probably too short to obtain 'reliable' values for Pu given its slow turnover. The study of Buldakov (1968) also used intravenous administration of Pu; this mode of administration may impact on the distribution and turnover of radionuclides in different organs for some radionuclides (e.g. Mayes et al., 1996).

6. Poultry and rabbits

6.1. Poultry tissues and eggs

Data from 28 experiments considering radionuclide turnover in different hen tissues/eggs were available to derive $T_{1/2}^{b}$ values (Table 1). In total, these studies provided data for eight radionuclides: ^{3}H, ^{54}Mn, ^{59}Fe, ^{65}Zn, ^{90}Sr, ^{131}I, ^{137}Cs, ^{238}U (Table 9). Most of

Table 9
Biological half-lives of radionuclide activity concentrations in tissues (other than muscle) of hens, geese and rabbits. Where only one component of loss was fitted this is presented under $T_{1/2}^{b(1)}$; R^2 is reported where given in the source reference. Half-lives calculated based on the data presented in the reviewed papers are given in *Italics*.

Nuclide	Tissue	α_1	Biological half-lives		R^2	Reference
			Fast loss, $T_{1/2}^{b(1)}$	Slow loss, $T_{1/2}^{b(2)}$		
Hens						
^{3}H	Whole Egg	1.0	1.7	–		Sirotkin (1987).
^{54}Mn	Whole Egg	1.0	15.4	–		Sirotkin (1987).
^{59}Fe	Whole Egg	1.0	13.5	–		Sirotkin (1987).
^{65}Zn	*Whole Egg*	*1.0*	*22.5*	–	*0.94*	*Based on Sirotkin (1987)*
^{90}Sr	Egg[a]	1.0	6.0	–	0.87	Panchenko et al. (1966)
^{90}Sr	Egg	0.96	1.5	17.0		Koldaeva et al. (1969)
^{90}Sr	Skeleton	0.93	4.4	142		Koldaeva et al. (1969)
^{90}Sr	Skeleton	0.8	13.0	160		Panchenko et al. (1966)
^{90}Sr	Skeleton	1.0	14.5	–	0.66	Panchenko et al. (1966)
^{90}Sr[b]	*Skeleton*	*1.0*	*139*		*0.76*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{90}Sr[c]	*Skeleton*	*1.0*	*41*		*0.92*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{90}Sr[d]	*Skeleton*	*1.0*	*29*		*0.91*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{90}Sr	Muscle	1.0	7.0	–	0.73	Panchenko et al. (1966)
^{90}Sr	Muscle	1.0	7.0	–		Buldakov et al. (1959).
^{90}Sr	Muscle	1.0	7.4	–		Panchenko et al. (1966)
^{90}Sr[b]	*Muscle*	*0.9*	*1.7*	*43*	*0.79*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{90}Sr[c]	*Muscle*	*0.9*	*2.5*	*52*	*0.86*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{90}Sr[d]	*Muscle*	*0.95*	*3.5*	*151*	*0.93*	*Based on Koldaeva and Sarapul'tsev (1968)*
^{131}I	Thyroid	1.0	3.6	–		Nizamov (1973).
^{131}I	Thyroid	1.0	4.3	–		Nizamov (1973).
^{131}I	Thyroid	1.0	5.3	–		Nizamov (1973).
^{137}Cs	Eggs	0.98	2.2	13.0		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Heart	1.0	2.5	–		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Kidney	1.0	2.5	–		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Liver	0.996	2.5	38.0		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	*Liver*	*1.0*	*18.7*		*0.96*	*Based on Shilov and Koldaeva (1978)*
^{137}Cs	Skeleton	0.995	2.6	38.0		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Skeleton	0.95	3.3	31.0		Shilov and Koldaeva (1978)
^{137}Cs	*Skeleton*	*1.0*	*24.8*		*0.94*	*Based on Shilov and Koldaeva (1978)*
^{137}Cs	*Heart*	*1.0*	*24.5*		*0.92*	*Based on Shilov and Koldaeva (1978)*
^{137}Cs	Lung	1.0	3.0	–		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Muscle	0.95	5.5	37.0		Koldaeva and Sarapul'tsev (1972)
^{137}Cs	Muscle	0.90	3.8	26.0		Shilov and Koldaeva (1978)
^{137}Cs	*Muscles*	*1.0*	*16.9*		*0.98*	*Based on Shilov and Koldaeva (1978)*
^{137}Cs	Spleen	1.0	2.4	–		Koldaeva and Sarapul'tsev (1972)
^{238}U	Soft tissues		2.4–4.1	73–112		Martyushov et al. (1984).
Geese						
^{137}Cs	Blood	1.0	2.9	–		Astasheva et al. (1992).
^{137}Cs	Heart	1.0	3.8	–		Astasheva et al. (1992).
^{137}Cs	Kidney	1.0	2.8	–		Astasheva et al. (1992).
^{137}Cs	Liver	1.0	4.8	–		Astasheva et al. (1992).
^{137}Cs	Lung	1.0	19.8	–		Astasheva et al. (1992).
^{137}Cs	Muscle	1.0	10.8	–		Astasheva et al. (1992).
Rabbits						
^{65}Zn	Whole-body	1.0	23–30			Avrunina (1965).
^{90}Sr	Muscles	0.96–0.98	1.4–2.4	21–27		Annenkov (1967)
^{137}Cs	Muscle	1.0	23–25			Kurliandskaya (1957).
^{137}Cs	Skeleton	1.0	37.0			Kurliandskaya (1957).

[a] Egg content.
[b] Cocks aged 23 d at the time of radionuclides administration.
[c] Cocks aged 60 d at the time of radionuclides administration.
[d] Cocks aged 155 d at the time of radionuclides administration.

the research studied excretion of ^{137}Cs from various poultry tissues such as muscle, liver, thyroid, offal and eggs. Both two and one component loss models were used to describe the data from poultry (Table 9).

For ^{90}Sr, the longest $T^b_{1/2}$ values were for bone as for all other animal types reported here. For other tissues, such as muscle and liver, both fast and slow $T^b_{1/2}$ values for ^{90}Sr were smaller than those for bone. The fast $T^b_{1/2}$ for ^{137}Cs in muscle ranged from 3.8 to 5.5 d and the slow $T^b_{1/2}$ varied from 26 to 37 d (Koldaeva and Sarapul'tsev, 1972; Shilov and Koldaeva, 1978). Similar fast and slow $T^b_{1/2}$ were reported by the same authors for both bone and liver, whereas for all other tissues (spleen, kidney, heart and lung) one component models were fitted with $T^b_{1/2}$ values ranged from of 2.4–3.0 d.

Ekman (1961) estimated two components of loss for radiocaesium from the whole-body of hens with $T^b_{1/2}$ values of 1.1 d and 27 d. Ekman also presents two component $T^b_{1/2}$ values for a number of hen tissues (heart –1.7 d and 16 d, kidney – 0.3 d and 16 d; liver – 1.5 d and 18 d) with a single component for lung (16 d). Ekman (1961) also estimates $T^b_{1/2}$ for radiocaesium in three individual hen muscles; gastrocnemius (leg) muscle had a two component $T^b_{1/2}$ of 2.7 d and 20 d which is similar to Shilov and Koldaeva (1978) whereas biceps (wing) and pectoralis (breast) had single component $T^b_{1/2}$ values of 56–59 d which are considerably longer than values reported in Table 9.

Two separate studies presented information on ^{131}I and ^{238}U respectively. Nizamov (1973) recorded a one component loss for ^{131}I in thyroid obtained for control hens in three different experiments on the evaluation of biological effects ($T^b_{1/2}$ ranged 3.5–4.3 d). Martyushov et al. (1984) reported $T^b_{1/2}$ values for ^{238}U from muscle of 2.4–4.1 d and 73–112 d for fast and slow components, respectively.

Astasheva et al. (1992) recorded the dynamics of accumulation and excretion of ^{137}Cs for various goose tissues during experiments with chronic administration of feed contaminated by ^{137}Cs after the Chernobyl accident. Measurements over 15 d during the decontamination phase of the study were available; a single loss model best described these data for all tissues. The $T^b_{1/2}$ for different goose tissues were in the range of 3–5 d, similar to those for hens. Exceptions were lung and muscle, for which $T^b_{1/2}$ values were c. 20 and 11 d respectively. Halford et al. (1983) estimated two component $T^b_{1/2}$ for the muscle of mallard ducks (*Anas platyrhynchos*) contaminated at a liquid radioactive disposal area to be 4.9 days (0.29) and 11 d (0.71) respectively, the latter being similar to the single component $T^b_{1/2}$ estimated by Astasheva et al. (1992) for muscle.

For whole egg, the fastest rates of decrease were observed for ^{3}H, ^{90}Sr and ^{137}Cs (1.5–2.2 d) whereas for ^{54}Mn (15.4 d) and ^{59}Fe (13.5 d) the $T^b_{1/2}$ values were longer (Table 9). For comparison, Mullen et al. (1976) estimated the biological half-life of ^{3}H in egg yolk to be 3.7 d and that of albumen (white) to be 3.4 d Voigt et al. (1993) estimated a single component $T^b_{1/2}$ value for ^{137}Cs of *c.* 3 d for whole eggs which is comparable with the values reported by Koldaeva and Sarapul'tsev (1972).

6.2. Rabbits

There are three sources in the Russian language literature giving limited data on $T^b_{1/2}$ values for rabbits. Kurliandskaya (1957) reported a single component $T^b_{1/2}$ of ^{137}Cs in rabbit muscle of 23–25 d, with a value for bone of 37 d (Table 9). There are some studies in the international literature reporting $T^b_{1/2}$ of ^{137}Cs in rabbits. Jandl and Sladnikov (1991) estimate $T^b_{1/2}$ values for rabbit muscle to be 1.5 d (0.66) and 66 d (0.34) following oral administration of hay contaminated by Chernobyl fallout for 24 days. Battiston et al. (1991) fed alfalfa meal, also contaminated by Chernobyl fallout, for 42 days and estimated a one component $T^b_{1/2}$ value for rabbit muscle of 11 d Semioshkina et al. (2007) reported data on administration of aqueous ^{137}Cs to rabbits for 42 d, estimating a single component $T^b_{1/2}$ value of 7 days. The Semioshkina et al. (2007) value appears short compared to all of the other values.

7. Discussion

When comparing the $T^b_{1/2}$ values from different studies there is a need to consider the fractions lost in each compartment as well as the $T^b_{1/2}$ values.

For cow milk, the $T^b_{1/2}$ values derived for different radionuclides (Table 1) tend to be similar with values of approximately 2 d describing the decrease of all radionuclides in cow's milk after a single administration.

Radionuclides with the shortest $T^b_{1/2}$ in animals are those which accumulate in soft tissues, such as ^{99}Mo, ^{132}Te, ^{137}Cs, ^{106}Ru etc., followed by radionuclides associated with proteins and colloid complexes ^{140}La and ^{144}Ce, and the longest $T^b_{1/2}$ occurring for those radionuclides deposited in bone such as ^{90}Sr (Sirotkin, 1987).

Since biological half-lives reflect losses of radionuclides incorporated into the organism, the effect of the chemical form of an administrated radionuclide is unlikely to be a major factor in the longer-term in many circumstances. However, the short-term behaviour can be affected by the form in which radionuclides are administered and in part this may also be influenced by experimental protocol. Some animal tissues accumulate and retain certain radionuclides to a relatively high degree, e.g., thyroid gland (^{131}I) and bone (^{90}Sr). The loss rates from such organs will therefore influence values of $T^b_{1/2}$ values in other organs, especially the second, slower component of loss (e.g. see Beresford et al., 1998a).

Sirotkin et al. (1972a, 1987) reported different behaviour of ^{131}I given as a single administration with water and with feed (Tables 2 and 4). Absorption of ^{131}I administered with feed appears to have been slower than that administered in water perhaps reflecting gut passage time. The time taken to reach peak radionuclide activity concentrations in tissues (Table 2), the magnitude of the peak concentrations and apparently subsequent losses of radionuclides all differed (see Tables 2 and 4).

7.1. Age

In general, $T^b_{1/2}$ values of radionuclides in animal tissues are shorter for younger (smaller) animal. This may be expected due to: (i) faster metabolism of young animals, and (ii) to some extent the dilution of radionuclides in the body of animals because of their faster growth rate. However, the data for the effect of age are not consistent across all of the experiments.

Some of the evidence for the longer $T^b_{1/2}$ with increasing age was reported for ^{137}Cs by Sirotkin (1987) from a single administration experiment. This gave $T^b_{1/2}$ values in the bone of 26 d in

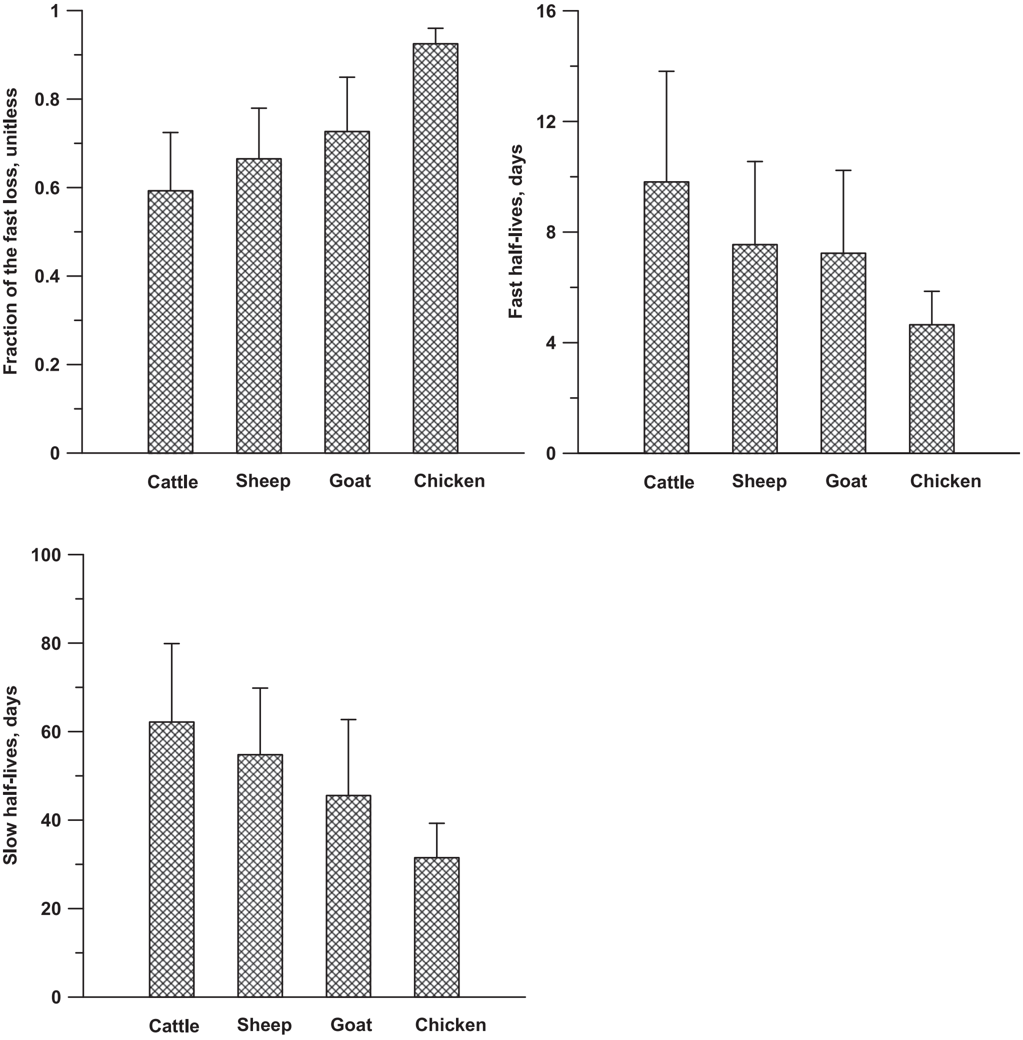

Fig. 2. Parameters for two loss exponential model of ^{137}Cs excretion from muscles of cattle, sheep, pigs and poultry.

new-born calves (at the time of the start of the experiment) and of 56 d in calves that were 10 months old when ^{137}Cs was administered. Based on direct measurements of the dilution due to tissue growth, the authors suggested that the loss of ^{137}Cs was driven mainly by rates of biological excretion from the tissues.

Similar evidence was observed in an experiment with sheep of different ages by Buldakov and Burov (1967) who reported faster excretion of ^{144}Ce from the liver of sheep aged 20–25 d ($T^b_{1/2}$ for a single exponential loss rate of 62.5 d) compared with sheep aged 180 d ($T^b_{1/2}$ of 94.5 d) and with sheep aged 1.5 years ($T^b_{1/2}$ of 142 d). Data demonstrating effect of age were given also for the skeletons of sheep of different ages. All these $T^b_{1/2}$ values for liver are considerably shorter than that those estimated by Beresford et al. (1998a) ($T^{b(1)}_{1/2} = 88$ d; $T^{b(2)}_{1/2} = 1900$ d) in the liver of sheep aged 5 months at the time of administration.

Data from Koldaeva and Sarapul'tsev (1968) were fitted with a single exponential expression for loss of ^{90}Sr from skeleton and muscle of chickens aged 23, 60 and 155 d at the time of radionuclide administration. A clear tendency for longer half-lives for older birds was found for both tissues (see Table 9).

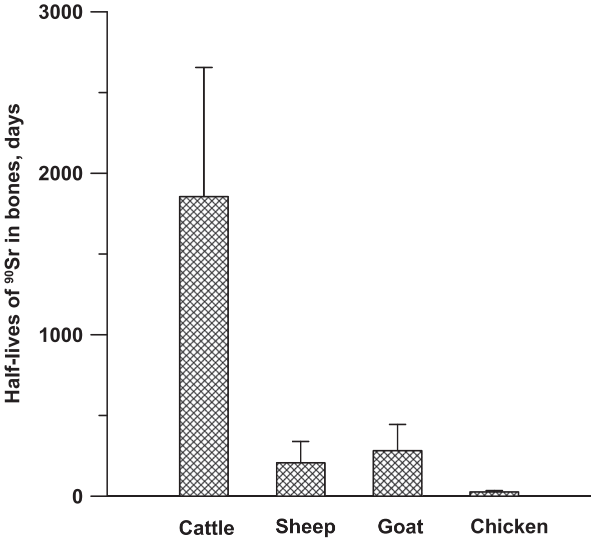

Fig. 3. Biological half-lives of ^{90}Sr loss from bones of cattle, sheep, pigs and poultry.

7.2. Variation between species

There are considerable differences among species which are likely due to variations in metabolic rates for cattle, sheep, pigs and poultry (Fig. 2). Generally, $T^b_{1/2}$ for ^{137}Cs in muscle for both the fast and slow losses are longer for larger animals i.e. $T^b_{1/2}$ declines in the order cattle > sheep and pigs > poultry. This arises because metabolic rate decreases with increasing body size (see Beresford and Vives I Batlle, 2013). Also, the fraction of the fast loss tends to be higher for poultry than for pigs and sheep, whilst the lowest fractions were observed for cattle. Similar trends in variations in $T^b_{1/2}$ with animal species were also observed for ^{90}Sr losses from bone (Fig. 3).

7.3. Variation between tissues

There are clear differences in $T^b_{1/2}$ for some radionuclides in different tissues due to different tissue metabolism of the chemical element or its analogue. For some radionuclides (e.g. Sr and I (Crout et al., 1998, 2000) retention is controlled by dietary supply and the requirement for these elements in different tissues and to support lactation. In the longer term the main accumulating organ controls the half-life in other tissues (e.g. Beresford et al., 1998a).

7.4. Experimental factors

For many radionuclides data reviewed in this paper were from short-term experiments. Short-term experiments have limitations as the data acquired do not capture different components of loss and only a single value of $T^b_{1/2}$ can be estimated for any given tissue. Consequently, derived $T^b_{1/2}$ values may under-estimate the rate of loss (and consequently over estimate activity concentrations) in the short-term but over-estimate the rate of loss in the longer-term. However, data from such short-term experiments may give an approximation of change in activity concentrations following accidental releases when most of the dose to humans can occur (the applicability of such data may be limited to a time period approximating to the length of the study from which they were derived). Therefore, we have included such data within the paper.

Data reviewed in the paper are from both chronic and single administration studies. The different experimental protocols may have some effect on the relative contributions of the different components of loss. Similarly, the degree to which animals chronically administered radionuclides have reached equilibrium may affect the estimated half-lives, as indeed may the metabolic status of the animal. Biological half-lives assessed based on the experiments with single administration may be more relevant for the evaluation of radionuclide behaviour in animals in non-equilibrium (accidental) situations. Biological half-lives assessed based on the data from continuous exposure experiments may better reflect turnover in animals which have been consuming contaminated diets for prolonged periods and can be more effectively used for remediation planning.

Some of the studies described in the paper used radionuclides with short half-lives, consequently longer-term losses could not be accurately estimated from these studies.

Sampling regime obviously impacts on the resultant $T^b_{1/2}$ values derived, for instance more frequent sampling soon after radionuclide administration will allow better determination of the short-term dynamics.

8. Conclusions

There is no comprehensive review of biological half-life values available within the literature and data compilations such as IAEA (2010). This is a considerable omission in our knowledge. Although some of the data presented here have limitations (i.e. as a consequence of experimental protocol) they add considerably to the pool of information available on the dynamics of radionuclides in a range of farm animals.

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