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DISTRIBUTION OF AND DISCRIMINATION AGAINST NATURALLY
OCCURRING RADIUM - 226 IN SWINE

by

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INTRODUCTION

The central position held by radium-226 in the development of radiotoxicology make it an isotope worthy of further study. Even though in recent years our knowledge of toxicology of radioisotopes has advanced rapidly along many fronts, the wealth of data on human and animal exposure to radium-226 requires the use of a "radium standard" for evaluation of hazards due to internal emitters. Thompson (1) has stated "The central position of radium in consideration of internal emitter hazards is the result of some hundreds of human exposures in which the metabolism and biological effects of radium may be studied". The 1954 ICRP recommendations (2) still use the maximum permissible body burden for radium of 0.1 μ Ci as the basis for assigning maximum permissible body burdens for other alpha-emitters deposited in bone. A number of authors have investigated the metabolism or toxicity of radium in humans and animals. Silberstein (3) reviewed the literature on radium poisoning through 1945. Dougherty et al. (4), Stover et al. (5), Van Dilla et al. (6) Schulert et al. (7), Morris and Kisielewski (8), Marshall (9), and many others have reported

on the metabolism of Ra-226 either alone or in comparison with other elements.

Although many authors have reported on the radium-226 content of the atmosphere, of food and water, or of man and animals (10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25), finding from 10^{-8} to 10^{-15} gm. Ra-226/gm in vegetable products and 10^{-10} to 10^{-18} gm. Ra-226/gm in animal tissue, atmosphere, and water, few authors (26, 27, 28, 29, 30 and 31) have investigated the distribution within the body or skeleton.

Physiological similarities between swine and humans suggested that an investigation of the metabolism of and discrimination against radium-226 in swine might furnish information that would correlate with the human case. The barriers to radium-226 at physiological boundaries were investigated by calculating "observed ratios" (OR's), in a manner analogous to those used by Comar in investigations of strontium-90, to compare radium-226 with other divalent cations.

Power function models calculated from the data were compared to power function models calculated for human and other species to determine correlation with the human model. The ranges of radium burden found required the use of a normalizing system to compare the various skeletal bones more accurately. The system used and the results ob=

tained are presented and discussed.

MATERIALS

Animals from two sources were used for the study. Eight, 6 month old barrows (males) were obtained from the Swine Division, College of Agriculture, University of Illinois, Urbana. These barrows were brothers or half-brothers of mixed breeding. They had been farrowed at about the same time, kept in the same lot after weaning, and received the same general diet since weaning. All eight animals were removed from the lot at the same time, four being placed in swine metabolism cages for one week, then slaughtered, the other four held on clean concrete for a week, then placed in metabolism cages for a week and finally slaughtered.

While in the metabolism cages the animals were fed twice a day, once in the morning, a second time about 8 hours later. The same feed used to feed the animals while they were running in the lot was mixed with water in a 1 to 1 ratio and fed as a slop. A record was kept of the amount of feed consumed by each animal each day. The urine and feces produced each day were collected and then all collections were pooled for each animal to get the output for the seven-day period. Samples of tissues, bone, and blood were obtained for each animal at slaughter.

A second group of eight swine, mature sows (females), also of mixed breeding, was obtained from a farm near Frank-

fort, Illinois. These animals were sisters or half-sisters and all were about 22 month of age at the termination of the study. They had been kept on the same farm, receiving identical diets for 18 months, and then were transferred to a farm near Goodenow, Illinois. All animals received the same diet at Goodenow, but it differed from the Frankfort diet. These sows were bred at about the 16th month and farrowed between $3 \frac{1}{2}$ and $4 \frac{1}{2}$ months later. Sow # 7 died during farrowing and was replaced with sow # 9, which was available in case of such an eventuality.

Samples of feed and water taken for each location at random times during the study were pooled. Neonate piglets were obtained at farrowing and killed before they could nurse, so they were considered to be very mature fetuses.

Samples of milk were obtained from 5 of the 8 sows between four and five weeks after they farrowed. Samples of tissues, bone, and blood were obtained for each animal at the time of slaughter.

METHODS

The radium-226, calcium, and phosphorous content of all samples was determined using techniques judged to be simplest and best for the purpose.

Radium - 226 : The basic method used to assay for radium-226 content has been described in another paper (32)

as a modification of the emanation assay technique developed by Lucas (14, 33).

The basic system is for the de-emanation and collection of radon-222 and is shown in figure 1. Samples assayed using this system were first charred to a carbonaceous mass at low temperature (500 - 600°F) in a restricted air supply, then ashed in fused silica boats at 600°C to 900°C in a furnace with a controlled air supply.

Of these samples, ashed bone samples were dissolved in hot concentrated nitric acid, diluted with 1 M nitric acid and transferred to empty generator flasks. All other ashed samples were dissolved in concentrated hydrochloric acid and diluted with 1 M hydrochloric acid, then transferred to empty generator flasks.

A modification of this radon-222 collection system is shown in figure 2. It was used to assay large volume samples. Water and urine samples were acidified with 50 to 100 ml of concentrated nitric acid before assay. Blood samples, drawn with tetrasodium EDTA as an anticoagulant, were not acidified, but 1 to 4 ml of octanoic alcohol were added to prevent foaming.

The radon-222 was collected for assay 4 to 14 days after the generator flask had been de-emanated and closed. Radon trapped at dry ice-alcohol temperature in the radon collection trap shown in figure 1 and 2 was transferred to a counting chamber (Fig.3) using the transfer system shown in

figure 4. The radon was transferred using six washes of 16 cc of aged helium as the transfer gas.

The radon-helium filled counting chamber's were placed window down on the face of a photomultiplier tube (air-coupling) and counted. The amount of radon-222 (0.9878 times the amount of radium-226 (34)) present was calculated using a computer program developed by Henry F. Lucas, Jr., of the Radiological Physics Division, Argonne National Laboratory. This program contains an adjustment factor, called the "J" factor, as proposed by Lucas and Woodward (35) to compensate for deviation from Poisson Statistics in the counting.

Results are presented as femtocuries of radium-226 per gram of ash:

$$\left\{ \frac{\text{fCi. Ra}^{226}}{\text{gm. ash}} \pm \text{the 95\% confidence limits} \right\}$$

Calcium : The calcium content of all samples was determined using the method of Kingsley and Robnett (36). The high iron content of some samples interfered with this colorimetric method, so it was necessary to remove this interference. Although there are many ways to extract iron from solutions, many of them also remove calcium, eg. precipitation reactions. The approach using organic solvent extraction seemed most satisfactory (37). The extremely low pH of the solutions (pH 0 to 2) made it difficult to use many other systems. Three different extracting systems were tested.

- 1) Tri-iso-octylamine (TIOA) 20% in CHCl_3 ;
- 2) di(2-ethylhexyl)phosphoric acid (D2EHPA) 10% in toluene ;
- 3) 2,4 - pentanedione (acetylacetone) 20% in CHCl_3 . The acetylacetone- CHCl_3 system is similar to that used by Steinback and Freiser (38, 39), and it seemed to be the best tried. 10 ml samples were extracted with 5 ml portions of the acetylacetone- CHCl_3 mixture, by mixing well for 2 minutes, centrifuging, and removing the colored complex with the CHCl_3 layer. Samples were extracted 4 or more times with the acetylacetone- CHCl_3 mixture, then given a final wash with 5 ml of CHCl_3 by mixing for 1 minute, centrifuging, and removing the CHCl_3 layer. If the CHCl_3 was not nearly colorless, the sample was re-extracted with the acetylacetone- CHCl_3 mixture.

Recovery of calcium from calcium "spiked" test solutions was $100\% \pm 4\%$.

Calcium values are reported as milligrams of calcium per gram of ash:

$$\frac{(\text{mg. Ca})}{(\text{gm. ash})}$$

Phosphorous : The phosphorous content of all samples was determined using the Gomori Modification of the Method of Fiske and Subbarow (40, 41). The analyses were made using aliquots of the same solutions used for calcium determinations.

Phosphorous values are reported as milligrams of phosphorous per gram of ash

$$\frac{(\text{mg. P})}{(\text{gm. ash})}$$

R E S U L T S

The results of the assay for radium-226 content are presented in table 1 and 2. Table 3 lists the normalized skeletal values for radium-226 content in 8 skeletons so that they can be compared both within and between skeletons. Table 4 compares the per cent distribution between urine and feces of total radium-226 excreted in the 7 day collection period for the 8 Barrows. In these tables, and in all other places where possible, the mean value and 95 per cent confidence limits have been computed.

The criteria of statistics for small numbers of observations as suggested by Dean and Dixon (42) have been used for all calculations not done by computer. Their criteria have also been used at any time a value had to be dropped from the calculations.

In the bone samples analyzed for calcium and phosphorous content (128 samples) ; calcium content was 386.7 ± 61 mg. per gram of ash and phosphorous content was 178.8 ± 2.9 mg. per gram of ash, giving a Ca/P ratio of 2.16 ± 0.08 on a weight of Ca/weight of P basis. This Ca/P ratio is within the normal range and was computed to determine if there was any gross loss of calcium during ashing procedures.

Calcium contents were also determined for all other samples to allow calculation of OR's. Table 5 lists the OR's calculated in this study. Table 6 compares the Ra^{226} OR's calculated in this study with Sr^{90} OR's reported by other investigators (43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53).

DISCUSSION

The metabolism and metabolic fate of radium-226 is a complex function of accretion, retention, exchange, and diffusion across physiological boundaries. It has been suggested (5, 8) that the metabolism of radium and strontium is qualitatively the same as calcium, but quantitatively unique.

Marshall (9) has proposed a power function model to explain alkaline earth metabolism, including radium-226. In this model the alkaline earth metabolism is dominated by a complex system for deposition of calcium and calcium-like elements, especially into bone. Deposition of calcium occurs primarily as sub-microscopic crystals ($27 - 75 \text{ \AA}$ in diameter) of hydroxyapatite in bone. The deposition of calcium from blood will occur in any calcifiable matrix and mobilization occurs when the matrix is resorbed. Smaller amounts of calcium might be deposited in or mobilized from extracellular fluids, crystal surfaces, even crystals deep within bone. All tissues contribute calcium within the homeostatic system of

the body. The various exchange processes involving calcium, and alkaline-earths, thus form a complex distribution system, the pathways of which have turnover times of various durations. An alkaline-earth cation, therefore, may be absorbed, then immediately excreted. Or, it may leave the blood for another locus within the body, to return to the blood in minutes, days, or even years.

The distribution of radium-226 in the tissues, secretions, and excretions of the animals studied is shown in Tables 1 and 2. The most notable feature observable in Tables 1 and 2 is the variation both between and within animals. The values for the bones of the eight sows are high because they reflect the radium-226 content of their earlier diet at Frankfort. In calculating OR's later in this paper, the values for Frankfort diet are used to compute the ratios for the sow's skeletons.

Since the sows were on the Goodenow diet for 56-90 days the soft tissues and fetuses had the opportunity to equilibrate with this new diet even though the sow's bones had not yet equilibrated. So, if the bones of the neonate are used instead of the maternal (sow) skeleton and are considered to be equivalent to the barrow bones, some interesting observations are possible. The radium-226 content per gram of ash is about the same in blood and bone while the content in muscle is about one half of this value. In contrast, the calcium content per gram of ash is roughly the same in muscle and blood even

though there is about thirty-three times more calcium in bone. This is seen as gross evidence of the difference in radium-226 metabolism which will be more readily observed when the comparative OR's are considered.

In table 3, the bones of the skeletons of the eight sows have been normalized to allow comparisons between bones for all animals of the group. If the mean value of radium-226 content per gram of ash for the skeleton is taken as 100 %, then all other bones with the exception of the sternum, manus, pes and tail lie within ± 15 % of this value. This is in good agreement with our earlier findings (32) that all bones with the exception of ribs, skull, mandible, manus and pes were within ± 15 % of the skeletal mean. In this study the manus and pes are but slightly outside of the ± 15 % range.

This range of variation is in agreement with the report by Walton et al. (28) on the distribution of radium-226 in human bones. Both their findings and ours are, however, at variance with the report by Schubert et al. (7) who found a range of + 90% to -60% for the distribution of strontium-90 in human bones and Dubrovina et al. (54) showing a range of + 16% to - 31% for strontium-90 distribution, in goat and sheep bones.

We agree with Dubrovina et al. that :

- 1) - the activity of a part of bone cannot serve as a basis for estimation of the activity present in the entire skeleton, a whole bone must be used ;

2) - the ratio between radioisotope content per gram of calcium in individual bones and the radioisotope content of the skeleton varies with time (and with diet) and cannot be used to evaluate skeletal activity. A single whole bone can only be used to estimate, at that moment in time, the total skeletal activity within $\pm 15\%$ in the case of radium-226.

Table 4 presents the route of excretion of radium-226 by the eight barrows during the seven day period of a study. The mean values of $98.04 \pm 0.72\%$ voided in feces and $1.96 \pm 0.72\%$ voided in urine are much closer to values reported for humans (3) of 98% in feces and 2% in urine than to values reported for the rat, 81 - 88% in feces and 5 - 10% in urine (8). This comparison might not be valid since we have assumed that alkaline earth metabolism in the barrows was in equilibrium and that the excretion of radium-226 was the same as for a single dose given as a tracer. These values need to be verified by single dose oral and intravenous tracer studies. However, it seems as if there is an interspecies similarity in which swine may resemble the human in their radium metabolism.

Several investigators (55, 56, 57 and 58) have suggested the use of power function models in the study of the metabolism of radium-226. The power function model for retention of radium-226 has the general form :

$$R_t = At^{-b} \quad \text{where } t \geq A^{1/n} \quad 0 < b < 1$$

where :

A = fraction of assimilated dose retained when $t = 1$ day

t = time after assimilation of dose

$-b$ = slope of the linear log-log transform of the retention curve

R_t = fraction of assimilated dose retained t days after assimilation.

Data were not available from this study to employ the general model. However, it was possible to employ a modification developed by Hallden et al. (53) from the power function model for radium-226 first described by Norris et al. (59). To use data developed in this study to compute such a power function model it was further assumed that:

- 1) Human and porcine radium excretion patterns are similar (in this study it seemed to be true),
- 2) Absorption of radium-226 is identical in human and ^{porcine} ~~porcine~~ ne.

The expression for the power function retention model in swine then was :

$$R_t = C (1.12(t^x - 1) + 0.54) = 0.54 t^{-(1-x)}$$

where :

R_t = μ Ci of radium-226 in total body.

t = time in days.

C = μ Ci of radium-226 metabolized per day = 10% of radium-226 ingested per day.

x = slope of the linear log-log transform of the retention function.

For the barrows at equilibrium over a 180 day period, there was :

- 1) total body radium-226 = 15.072 ± 3.033 pCi ;
 and 2) total daily radium-226 consumption =
 8.09 ± 0.03 pCi ;

therefore :

$$15.07 \text{ pCi} = 0.81 \text{ pCi} (1.12(180^x - 1) + 0.54),$$

with

$$180^x = 17.34$$

$$x = 0.55$$

$$R_t = 0.54 t^{-0.45}$$

For the sows at equilibrium over a 480 day period on the special diet for sows, there was :

- 1) total body radium-226 = 214.785 ± 29.253 pCi ;
 and : 2) total daily radium-226 consumption =
 115.54 ± 2.53 pCi ;

therefore :

$$214.8 \text{ pCi} = 11.55 \text{ pCi} (1.12(480^x - 1) + 0.54),$$

with

$$480^x = 17.11$$

$$x = 0.46$$

$$R_t = 0.54 t^{-0.54}$$

The value derived with Hallden's method for the use of the power function model was for adult swine,
 $R_t = 0.54 t^{-0.54}$ and is similar to that for adult humans,
 $R_t = 0.54 \cdot t^{-0.52}$.

It is of course, possible that the assumption of 0.54 for the initial retention value at day one is incorrect since

values of 0.80 have been reported in rats (8) and 0.787 in dogs (6). However, substituting a value of 0.80 for 0.54 in the original equation transforms the power function model in swine to $R_t = 0.80 t^{-0.54}$. This new model still resembles in its slope, the human model more than that of rats, $R_t = 0.80 t^{-0.229}$ or dogs, $R_t = 0.787 t^{-0.198}$.

In the young swine the models for the two different initial retention values are : $R_t = 0.54 t^{-0.45}$ and $R_t = 0.80 t^{-0.45}$ respectively.

We presently incline towards the belief that the reduced slope observed in the young swine might be a reflection of increased accretion due to the rapidly enlarging skeletal volume.

Finally, we considered the presence of specific preferential barriers for radium-226 which can be estimated from calculations of OR's. Comar et al. (45) have extended the concept of OR's from the original double tracer scheme using calcium-45 and strontium-89, to include a single radiostrontium tracer in combination with stable calcium in equilibrium situations. Analogous OR's for radium-226-calcium can be computed, since on a steady diet both elements should be in equilibrium. The OR as used in this paper is as Comar used it, to denote the overall discrimination observed in the movement of the two elements across one or more physiological boundaries or barriers.

In this study variations in the ratio of radium-226 calcium in feed and in water should have been at a mi-

nimum since all rations were balanced and well mixed. Although, both the age of the animal and the length of time an animal is fed a given diet influence strontium-90 OR's (60, 61), the influence of these two factors on radium-226 OR's can not be measured adequately from our data. But, there is some evidence of such an influence in the bone-diet OR's and the power function models, when the young barrows and more mature sows are compared.

Active systems transporting calcium but not strontium have been reported (46, 62) and the existence of a unidirectional barrier has been observed (63). However, we do not have any information of this nature about radium.

• It has been shown that calcium, strontium and cesium readily cross the placenta reaching a steady state 16 to 30 hours after administration of a single tracer dose (47, 64, 65 and 66). In the steady state the ratio of the element in maternal blood to the element in fetal blood approaches unity. Intimate contact of maternal and fetal circulations has been observed even in the porcine placenta, in electron microscopic investigations (67, 68 and 69). Thus, it is reasonable to believe that radium-226 will cross the placenta with an ease equal to other radioisotopes. Therefore, the radium-226-calcium ratio of maternal blood has been considered to be the same as that ratio for fetal blood. Our data supports this view.

OR's calculated in this study are presented in

Table 5. Some comments on this data are in order. Comparable tissues of the sows and barrows agree reasonably well, but do have wide individual variability. The blood-diet OR is approximately 0.67 while the bone-diet OR is about 0.015 indicating that there is a slight discrimination against radium-226 at the intestinal wall but a 30 fold discrimination between blood and bone. The high OR's shown by skin and fat and lung may be only a reflection of the high blood content of these organs. However, this explanation suggest that there should be a high value in the liver also. But this is not observed. Further study of this question is indicated.

There is definite evidence of several preferential barriers for radium-226 in the OR's. But they are not always in the same direction as for strontium. A comparison of strontium-90 and radium-226 OR's is presented in Table 6. Radium-226 is about 10-20 fold lower than strontium-90 in bone, milk and urine when it is compared either with the diet or plasma. It is about 2 - 6 fold lower in the fetus when compared to diet or plasma. The plasma and feces-diet OR's are about equal to those for strontium or slightly higher. This is also true the fetus-dam OR.

The difference in radium-226-calcium and strontium-90-calcium OR's is, with two exceptions, a difference in the magnitude of the discrimination against the isotope. Of the two exceptions, the difference between the

fetus-dam OR's for radium and strontium may be an artifact. Recently, Mole (70), in discussing stable strontium, stated, "The ratio of perinatal bone to maternal bone will be a biased estimate of placental discrimination to the extent to which maternal plasma and maternal bone are not in equilibrium during pregnancy". He found an average strontium-90 OR of 0.7 for fetus to dam, and in one case reported a fetus-dam OR of 0.9 for stable strontium when the strontium-90 OR was 2.5. This clearly shows that, unless the maternal bone and plasma are in radioactive equilibrium, the fetus-dam OR will be biased and diverge from the placental discrimination. We would predict, almost no discrimination.

On the other hand, the difference between radium and strontium urine-plasma OR's is particularly intriguing since it suggests that there may be a substantially different physiological mechanism involved in the kidney where these two ions are concerned. The radium-226-calcium OR obtained for urine-plasma discrimination in this study implies either reduced glomerular filtration or increased tubular resorption of radium relative to strontium and calcium. In order to account for the divergence of OR's. The mechanisms of this apparently anomalous behaviour merit further study.

Such comparisons clearly demonstrate that there are real differences in the metabolism of radium-226 and of strontium-90 by swine. One can speculate that the similarity in plasma-diet ratios reflects a similar mode of

intestinal absorption.

The differences that one sees in radium-226 and strontium-90 OR's are undoubtedly due to many factors. These may include differences in solubility and/or diffusion constants, inability of biological chelating agents to chelate radium, differences in binding capacity of proteins for divalent cations of different atomic size, specificity of transport systems or hormone regulation, etc. (71). Whatever they may be, many interesting questions of relative importance are still to be answered.

CONCLUSIONS

From the data obtained in this study, it can be demonstrated :

- 1) The distribution of radium-226 in the porcine skeleton is relatively uniform with the exception of the manus, pes, sternum, and tail. A whole individual bone has a radium-226 content per gram of ash within $\pm 15\%$ of the skeletal mean.
- 2) The concentration of radium-226 within the tissues of the porcine body is extremely variable. Only whole bones can be used to estimate skeletal or whole body radium-226 content.
- 3) A power function model for retention of radium-226 by swine can be calculated with a value resembling that for the human, i.e., porcine $0.54t^{-0.54}$ versus human $0.54t^{-0.52}$.

4) Radium-226 is associated with calcium and strontium in the metabolism of divalent cations, but is confronted by a selective barrier at physiological boundaries where :

- a) It passes through the porcine placenta with little or no discrimination much as do calcium, strontium, and cesium.
- b) Passing from diet to bone it is discriminated against 10 - 20 fold more than strontium-90 and 50 - 100 fold more than calcium.
- c) Passing from diet to milk it is discriminated against 3 - 8 fold more than strontium-90 and 33 fold more than calcium.
- d) Passing from diet to fetus it is discriminated against 2 - 10 fold more than strontium-90 and 50 fold more than calcium.
- e) Passing from diet to plasma or diet to feces there is no discrimination relative to strontium-90 values.
- f) Passing from diet to urine it is favored 5 - 20 fold over strontium-90.

Though this study has shown the existence of selective barrier^s for radium-226 when compared to some other divalent cations, the mechanism controlling these barriers is not much known. Much additional information is needed to elucidate the comparative mechanisms of divalent cation metabolism.

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Fig. 1

The modified radon collection system uses dry compressed air passed through a molecular sieve, a moisture trap and a radon trap as a source of dry radon-free air. A Pyrex generator flask of 500 or 1000 cc capacity is used to hold the sample solution. The generator flask is filled to between 20% and 80% of its total capacity. Moisture traps located between the generator flask and the radon collection trap, dry the radon bearing air from the generator flask so that water vapor will not poison the charcoal in the radon collection traps. A manostat flowmeter is included in the system so that the rate of flow of air through the system can be adjusted to 1 liter/min. All traps in the system were maintained at -70°C (dry ice/ alcohol) during use.

In use, the system started with only the by passes open so that ambient air could be cleared from the system. After the ambient air had been blown from the system, the collection trap by pass was closed and the radon collection trap opened, then the generator by pass was closed and the generator opened so that radon laden air passed from the generator to the radon collection trap. A total of 30 liters of air was passed through a 500 cc generator and 60 liters through a 1000 cc generator to assure complete transfer of radon to the radon collection trap.

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FIG. 2

A further modification of the radon collection system for use with large samples or CO_2 producing samples. The general mode of use is the same, but 1 to 5 gallon pyrex bottles are used as generator flasks. The increased liquid volume required addition of two large cold finger moisture traps so that original moisture traps used could extract the residual water vapor. If the sample evolved CO_2 , i.e. blood or urine, a CO_2 trap containing 300 ml of 4 Molar KOH was placed between the generator flask and the cold finger moisture traps. This additional trapping capacity was needed because both CO_2 and moisture could poison the radon collection trap.

A volume of air 2 times the volume of fluid in the generator flask would transfer 50% of the radon from aqueous solutions, while a volume of air 6 times the volume of liquid was required to transfer 50% of the radon from blood or plasma. Therefore, volumes of air 20 to 60 times the volume of fluid were used to quantitatively transfer the radon to a radon collection trap.

Irregularities in air flow required the use of a wet-flow gas meter after the manostat flow meter to measure the total volume of air through the system.

Fig. 3

Counting bottle used to count radon samples.

COUNTING CHAMBER

Fig. 4

Radon transfer system used to transfer radon sample from a radon collection trap to a counting bottle. A Sigma peristaltic pump, operated at 380 or 575 rpm, is used to transfer the 15 cc aliquots of helium carrier gas with the radon sample across the system to the counting bottle. Heating the sample-containing charcoal in the collection trap to 450+ 500°C drives the radon from the charcoal and facilitates transfer. Three aliquots of helium carrier transfer about 98% of the radon.

TABLE 1

Distribution of Radium ²²⁶ in Eight Sows, Expressed as : fCi Ra ²²⁶/gm ash ($\pm 95\%$ confidence limit where indicated).

Animal	1	2	3	4	5	6	8	9	Mean
Skull	51	37	45	54	45	37	53	34	45 $\pm$ 6
Mandible	50	34	48	50	47	40	51	31	49 $\pm$ 6
Scapula	47	38	45	51	43	35	48	33	46 $\pm$ 5
Humerus	60	41	52	54	51	44	52	36	52 $\pm$ 7
Radius and Ulna	57	36	47	52	47	41	50	38	48 $\pm$ 6
Manus	62	40	53	55	52	44	54	39	52 $\pm$ 7
Spine	47	42	46	51	53	46	55	38	46 $\pm$ 5
Ribs	47	39	43	49	47	36	47	30	45 $\pm$ 6
Sternum	39	37	35	44	43	34	51	30	38 $\pm$ 6
Pelvis	52	37	45	50	47	38	53	36	46 $\pm$ 5
Femur	57	41	48	48	48	43	54	40	48 $\pm$ 5
Tibia and Fibula	54	36	46	53	46	36	49	35	46 $\pm$ 6
Pes	61	40	54	49	52	44	51	38	50 $\pm$ 7
Tail	54	45	54	62	53	42	66	37	54 $\pm$ 8
Skeleton	51 $\pm$ 1	38 $\pm$ 1	45 $\pm$ 1	51 $\pm$ 1	48 $\pm$ 1	40 $\pm$ 1	52 $\pm$ 1	35 $\pm$ 1	46 $\pm$ 8
Neonate	10.4	7.4	6.5	6.4	10.2	12.8	7.7	15.5	9.0 $\pm$ 2.6

Pelvis	52	37	45	50	47	38	53	36	46± 5
Femur	57	41	48	48	48	43	54	40	48± 5
Tibia and Fibula	54	36	46	53	46	36	49	35	46± 6
Pes	61	40	54	49	52	44	51	38	50± 7
Tail	54	45	54	62	53	42	66	37	54± 8
Skeleton	51±1	38±1	45±1	51±1	48±1	40±1	52±1	35±1	46± 8
Neonate	10.4	7.4	6.5	6.4	10.2	12.8	7.7	15.5	9.0± 2.6
Milk		7.7			23	14	11	10	11.0± 7.8
Blood	6.2	7.2	8.2	4.8	6.8	6.6	8.8	10.9	7.0±1.8
Muscle	1.9	3.8	1.2	4.1	4.0	4.1	3.6	9.0	3.9±2.3
Fat and Skin	27	19	18	17	3.8	7.2	6.9	17	17.0±6.7
Lung	32	30	22	31	31	21	21	20	26.0±3.5
Liver	1.7	1.9	11.0 ^a	3.7	1.6	1.2	1.6	2.5	1.7±0.8
Heart	2.4	2.5	3.8	2.1	1.9	4.9	1.3	3.0	2.4±1.0
Kidney	4.7	17	20	4.7	5.6	3.7	5.3	5.9	5.4±4.7

Frankfort Feed 1198±64
Frankfort Water 400±13^b

Goodenow Feed 946± 15^b
Goodenow Water 48 ± 2^b
Water

a) not included in mean

b) fCi. Ra²²⁶/liter

TABLE 2

=====

Distribution of Radium²²⁶ in Eight Barrows, Expressed as fCi. Ra²²⁶/gm
ash (+ 95% confidence limits where indicated)

	U of I I - 1	U of I I - 2	U of I I - 3	U of I I - 4	U of I II - 1	U of I II - 2	U of I II - 3	U of I II - 4	Mean
Humerus	5.2	6.4	4.4	10.3	4.4	5.8	6.5	6.6	6.1 ± 1.7
Ribs	4.4	5.0	5.0	9.4	4.1	7.1	4.8	6.2	5.0 ± 1.4
Blood	5.0	2.8	12.8	9.2	11.5	4.8	16.4	6.5	7.9 ± 3.9
Muscle	5.5	1.8	5.4	3.5	7.8	1.4	4.5	1.0	3.0 ± 2.0
Gut	48	25	38	43	35	18	40	21	36.5 ± 8.7
Feces	776	676	917	806	476	342	495	475	536.0 ± 166.8
Urine ^a	172	219	99	81	152	98	114	73	107.0 ± 42.3
Feed		180 ± 5				204 ± 5			
Water ^a		136 ± 5				66 ± 2			

a) fCi. Ra²²⁶/ liter

TABLE 3

Distribution of Radium-226 in the Skeletons of Eight Sows when Normalized against the Skeletal Mean ^a.

ANIMAL	1	2	3	4	5	6	8	9	Mean $\pm$ t ₉₅
Skull	1.00	0.98	0.99	0.96	0.94	0.93	1.02	0.98	0.99 $\pm$ 0.04
Mandible	0.98	0.90	1.06	0.98	0.98	1.01	0.98	0.90	0.98 $\pm$ 0.05
Scapula	0.92	1.01	0.99	1.00	0.90	0.88	0.93	0.95	0.94 $\pm$ 0.04
Humerus	1.18	1.09	1.15	1.06	1.07	1.11	1.00	1.04	1.08 $\pm$ 0.05
Radius and Ulna	1.12	0.96	1.04	1.02	0.98	1.04	0.96	1.10	1.03 $\pm$ 0.05
Manus ^b	1.22	1.06	1.17	1.08	1.09	1.11	1.04	1.13	1.10 $\pm$ 0.06
Spine	0.92	1.11	1.02	1.00	1.01	1.16	1.06	1.10	1.08 $\pm$ 0.07
Ribs	0.92	1.03	0.95	0.96	0.98	0.91	0.91	0.97	0.94 $\pm$ 0.05
Pelvis	1.02	0.98	0.99	0.98	0.98	0.96	1.02	1.04	0.99 $\pm$ 0.02
Femur	1.12	1.09	1.06	0.94	1.01	1.09	1.04	1.16	1.07 $\pm$ 0.06
Tibia and Fibula	1.06	0.96	1.02	1.04	0.96	0.91	0.95	1.01	0.99 $\pm$ 0.04
Pes ^c	1.20	1.06	1.19	0.96	1.09	1.11	0.98	1.10	1.09 $\pm$ 0.07
Tail	1.08	1.22	1.19	1.20	1.11	1.06	1.26	1.07	1.15 $\pm$ 0.06

a) Normalized value calculated as : $\frac{\text{Ra}^{226} \text{ content of bone}}{\text{Mean Ra}^{226} \text{ content of skeleton}}$

b) The Manus is composed of : metacarpals, carpals and associated phalanges.

c) The Pes is composed of : metatarsals, tarsals and associated phalanges.

TABLE 4

Per Cent Distribution of Excreted Radium-226

Animal	Per cent excreted in urine	Per cent excreted in feces
Barrow I - 1	0.81	99.19
Barrow I - 2	1.24	98.76
Barrow I - 3	3.94	96.06
Barrow I - 4	2.44	97.56
Barrow II- 1	2.60	97.40
Barrow II- 2	3.24	96.76
Barrow II- 3	1.48	98.52
Barrow II- 4	1.07	98.93
Mean	1.96 ± 0.72	98.04 ± 0.72

TABLE 5

Observed Ratios for Radium-226 in Swine

Barrows			Sows		
Precursor Sample	Diet	Blood	Precursor Sample	Diet	Blood
Humerus	0.012±0.003	0.021±0.014	Humerus	0.021±0.003	0.031±0.009
Rib	0.010±0.003	0.020±0.014	Rib	0.028±0.002	0.029±0.008
Blood	0.704±0.416	-	Blood	0.638±0.084	-
Muscle	0.304±0.165	0.330±0.196	Milk	0.028±0.015	0.044±0.022
Gut	1.019±0.203	1.442±0.288	Muscle	0.200±0.088	0.302±0.136
Urine	0.204±0.061	0.362±0.471	Skin & Fat	0.322±0.085	0.508±0.172
Feces	2.278±0.579	3.236±0.822	Lung	0.334±0.120	0.598±0.166
			Liver	0.072±0.025	0.112±0.069
			Heart	0.037±0.014	0.062±0.022
			Kidney	0.109±0.028	0.165±0.079
				Diet	Dam
			Neonate	0.018±0.005	0.882±0.391

Observed ratios computed as follows :

- 1) The number of femtocuries of radium-226 per gram of calcium in the sample is called the radium-calcium ratio (Ra/Ca)
- 2) The radium-calcium observed ratio (O R) is,

$$\text{OR} = \frac{\text{Ra/Ca of Sample}}{\text{Ra/Ca of Precursor}}$$

TABLE 6

Comparison of Observed Ratios for Radium-226 in Swine Computed in this Study with Observed Ratios Reported for Strontium-90.

	Strontium-90 observed Ratios in human and other species (43, 44, 45, 46, 47, 48, 49 and 50)	Radium-226 observed ratios in this study
Bone - Diet	0.210 - 0.350 0.170 - 0.190 in Swine (51)	0.010 - 0.021 ^a
Plasma - Diet	0.180 - 0.520	0.638 - 0.704
Milk - Diet	0.074 - 0.160	0.028 -
Fetus - Diet	0.080 - 0.170 0.030 in Swine (52)	0.018 ^b
Urine - Diet	1.1 - 4.3	0.204
Feces-Diet	1.2	2.278
Milk - Plasma	0.400 - 0.80	0.044
Fetus - Plasma	0.490 0.120 in Swine (52)	0.028 ^b
Urine - Plasma	7.4 - 16.0	0.362
Fetus - Dam	0.400 - 0.710	0.882 ^b

a) Hallden et al. (53) reported an OR bone-diet of 0.015 - 0.016 for radium-226 in humans.

b) Neonate values were used. These animals were killed immediately after birth.