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PLUTONIUM MICRODISTRIBUTION IN HUMAN BONE

by

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Abstract:

The amount and location of plutonium in bone from three humans injected during the mid-1940's has been studied by autoradiography and alpha particle spectrometry. Concentrations are similar on endosteal surfaces, Haversian canal surfaces and periosteal surfaces of long bone midshafts 17 months after injection. Endosteal surface concentrations are higher in the axial skeleton than in the appendicular skeleton 15 and 17 months post injection. For dosimetric purposes, volume deposits may be considered to be "infinitely thick" whereas surface deposits may be considered to have zero thickness. Secondary surface deposits are dosimetrically important, even when the plutonium is almost completely deposited in bone volume.

Introduction

With the consent of the next-of-kin, we have been able to exhume the remains of four persons injected with plutonium during the mid-1940's (Du72,La50). Three of these, a 20-year old woman with a 17-month burden (case 40-010), a 65-year old man with a 15-month burden (case 40-015) and a 79-year old man with a 20.7-year burden (case 40-001) have proven suitable for microdistribution studies.

This paper deals principally with the determination of the amount and location of ^{239}Pu in bone and dosimetric applications of the data. From the familiar pattern of plutonium distribution seen in autoradiographs not long after injection (Sc76), we can define four kinds of deposits:

(1) Buried surface deposits - These are associated with bone surfaces which were exposed to plutonium and subsequently covered by new bone formation. They often appear as intense bands of fission tracks covered by bone layers which are several tens of microns thick.

(2) Labeled bone volume deposits (LV) - These are associated with bone volume which was formed when plutonium was present in the blood. Labeled volume produces a relatively high fission track density compared with unlabeled volume (UV). Tracks produced by the latter are due only to natural ^{235}U. Labeled and unlabeled volumes are always separated by buried surfaces.

(3) Bone surface deposits (S) - We include, in this category, only the deposits on the bone surfaces now in existence; deposits on buried surfaces are specifically excluded. Two subcategories are also important:

(a) Deposits on the surfaces of labeled volumes (S(LV)) - These begin to accumulate after bone formation stops. They are easy to recognize in the autoradiographs because the adjacent bone volumes show relatively high densities of fission tracks.

(b) Deposits on the surfaces of unlabeled volumes (S(UV)) - These accumulate on bone which was formed before injection. The adjacent bone volumes show relatively low densities of fission tracks in the autoradiographs.

Three of these: buried surface deposits, LV and S(LV) always occur together in the autoradiographs at what we call "burial sites". This happens because of the sequence of events which leads to the formation of a burial site: surface deposition, burial of the surface deposit by the overgrowth of new bone and finally deposition on the newly formed surface when growth stops.

We measure ^{239}Pu concentration by counting fission tracks in the various kinds of deposits (Sc76). In order to use the data in dose rate calculations, we must also measure the thicknesses of LV and S. The thickness of a labeled volume deposit is obtained by measuring the cross sectional area of labeled volume seen in the autoradiograph and the length of the buried surface deposit which lies adjacent to it (Sc76). Thickness is then computed as area divided by length. This

tends to underestimate the mean thickness when the band of tracks representing the buried surface has a very irregular shape. As will be explained later, this error has no impact on the dosimetry. Surface deposit thickness is measured by alpha spectrometry (Sc75). This method is capable of high accuracy and is well suited to these rather thin deposits.

Results and Discussion - Case 40-010

Concentration

The surfaces associated with different structural elements in bone and the surfaces in different parts of the skeleton appear to have different tumor susceptibility. For this reason, when we present our data, we distinguish between the surface types. In compact bone, we identify the endosteal surface, which lies at the interface with bone marrow, the Haversian canal surfaces and the periosteal surface. In cancellous bone, we focus our attention only on the endosteal surface because it is, by far, the most abundant of the three types.

In long bone midshafts, the plutonium appears to be deposited only as S(UV). Concentrations are presented in Table 1. There is little difference between the endosteal surface, the Haversian canal surfaces and the periosteal surface.

Table 1

^{239}Pu Surface Concentrations in Long Bone Midshafts

Type of Surface	Concentration*, pCi/cm^2
Endosteal	0.27 ± 0.07
Haversian Canal	0.24 ± 0.02
Periosteal	0.34 ± 0.07

* Averages and standard errors (n = 6) are shown for the six major long bones of the right arm and leg.

Examination of microradiographs shows very little resorption surface at the time of death. This observation and the low frequency of labeled bone volume leads to the conclusion that very little remodeling occurred in the midshafts between injection and death. The observed surface deposits are apparently primary deposits which accumulated between the time of injection and death without interruption by bone remodeling.

Table 2 presents concentration data for bone surface deposits (S) at the endosteal surfaces of the axial skeleton and the proximal femur metaphysis. Sampling of the axial skeleton was limited to the cervical, thoracic and lumbar vertebrae, the ilium and the pubis.

Table 2

^{239}Pu Endosteal Surface Concentrations in the Axial Skeleton and the Metaphysis of the Proximal Femur

Location	Concentration*, pCi/cm^2
Axial Skeleton	1.01 ± 0.10
Femur	0.36 ± 0.02

* Averages and standard errors. Axial skeleton (n = 5), femur (n = 4). Where bones occur in contralateral pairs, the right one was used.

A distinct difference exists between the axial skeleton and the proximal femur, the former containing about three times as much plutonium per unit area as the latter. Comparison with Table 1 shows the axial skeleton concentrations to be about four times those on the endosteal surfaces of the long bone midshafts. These differences are probably a reflection of the greater blood circulation through the axial skeleton than through the appendicular skeleton. It is unlikely that they are due to some difference in the chemistry of bone surfaces in these regions.

In contrast to the long bone midshafts, there is much evidence of remodeling of the endosteal surfaces in the axial skeleton and the autoradiographs are rich with burial sites. Concentration data are shown in Table 3.

Table 3

^{239}Pu at Endosteal Burial Sites in the Axial Skeleton

Type of Deposit	Concentration*
Buried Surface	2.32 ± 0.28 pCi/cm^2
S(LV)	0.40 ± 0.07 pCi/cm^2
LV	105 ± 17 pCi/cm^3

* Averages and standard errors (n = 5).

Note that buried surface deposits are about six times as intense as S(LV) and S(LV) have only about 40% the intensity of S (Table 2). Since the concentration in S is an average of the concentrations in S(LV) and S(UV), the data imply that S(UV) are more intense than S and also more intense than S(LV). These differences in concentration reflect the accumulation histories of the different deposits: the plutonium in buried surface deposits began to accumulate shortly after injection, when the blood level was high, and continued until the surface was buried by bone formation. Plutonium in S(LV) began to accumulate when bone formation stopped, no earlier than a couple of months after injection and continued until death. During this entire period, the blood level was low. Plutonium in S(UV) accumulated between injection and death during periods of both high and low blood level. Although the formation of these deposits was probably

interrupted by resorption, this did not alter the basic intensity relationships brought about by exposure to high and to low blood levels. Were exposure to low blood levels to continue long enough, the intensity of S(LV) might eventually exceed that of the buried surface deposits. However, years more accumulation would probably be required for this to occur and the likelihood is small that the average concentration in S(LV) would not be substantially reduced by resorption during that time.

For comparison with labeled volume deposits, the concentration, if all of the skeletal plutonium were uniformly distributed throughout the bone volume, would be about 150 pCi/cm^3.

Deposit Thicknesses

Data on deposit thicknesses are presented in Table 4. The data for bone surface deposits were collected from endosteal surfaces of long bone midshafts.

Table 4

Deposit Thicknesses

Type of Deposit	Thickness, μm
LV	52 ± 2*
S	<3

* Average and standard error (n = 7).

Since the range of a ^{239}Pu alpha particle in bone is 23 μm, the labeled volume deposits are "infinitely thick" for the purposes of dose-rate calculation and also shield the surface cells from the buried surface deposits. Thus, although the method for determining the thickness of a labeled volume deposit tends to underestimate the true mean value, dosimetric calculations are unaffected.

No attempt has been made, so far, to determine the surface deposit thickness more precisely than shown because the uncertainty has little effect on the calculated dose rate. If the surface deposits were exactly 3 μm thick, the dose rate would be just about the same as if they were one atomic layer thick. Because of this, we assume a deposit of zero thickness whenever a dose-rate calculation is made.

Dose Rate

The S(LV) are secondary deposits which begin to form after the primary deposit has been buried. As the skeleton undergoes remodeling, the primary deposits gradually disappear and the plutonium becomes deposited more and more in secondary surface deposits and in the adjacent volume. The question then arises as to which have more dosimetric significance, the S(LV) or the LV. Using the data of Table 3, dose rates from both were calculated and are

presented in Table 5. It is clear that surface deposits contribute a far greater dose rate than do the volume deposits.

Table 5

Dose Rates* at Sites of Burial

Type of Deposit	Dose Rate
S(LV)	34 mrad/day
LV	6 mrad/day
Total	40 mrad/day

* Average over a 10 μm thick layer of tissue adjacent to the endosteal surfaces.

Since the surface continues to accumulate plutonium, its contribution to dose rate would continue to increase, further diminishing the importance of the LV.

The S(LV) in Table 3 are one-sixth as intense as the buried surface deposits but may well have been in position to irradiate surface cells considerably longer than the buried deposits were. Thus, the secondary deposits may well be as significant a source of accumulated dose, 17 months post injection, as the primary deposits were and cannot be ignored when considering the dosimetry of plutonium in bone.

Results and Discussion - Cases 40-015 and 40-001

Case 40-015

By comparing track densities in different autoradiographs, we find that endosteal surfaces (S) in the iliac crest have higher concentrations than in the midshafts of the tibia and humerus and much higher concentrations than in the proximal metaphysis of the humerus; endosteal surface concentrations (S) in the midshaft tibia are approximately equal to those in the midshaft humerus. These same relationships are true also for Case 40-010. Both cases had burden times of about 1.3 years but differed in sex and age at injection; in addition, 40-010 suffered from Cushing's Syndrome, a disease which affects bone remodeling. Despite these differences, it appears that the plutonium is distributed similarly in the two cases. It may well be that injected plutonium follows the same basic early distribution pattern in all adults, a pattern defined, in part, by the blood circulation.

In addition, we have measured the thickness of the deposit on the endosteal surfaces of long bone midshafts and find it to be less than 3 μm. The same result was found for Case 40-010.

Case 40-001

This case had a long burden time, 20.7 years, compared with the others. Because of this, we anticipated and found a relatively

large fraction of the plutonium in LV. In fact, examination of the autoradiographs leads one to believe that the plutonium is entirely in LV and that no surface deposits exist at all. However, alpha particle spectrometry reveals that a secondary deposit is still present on the endosteal surfaces of cortical bone and dose rate calculations indicate that it contributes more than 20% of the terminal dose rate.

Unfortunately, this person had been cremated and surface fragments flake off of bone ash. Since flaking may have occurred after cremation, the surface deposit may actually have contributed considerably more than 20% of the total dose rate at death. These observations suggest that the secondary surface deposit is dosimetrically significant after 20 years and again emphasize the importance of secondary surface deposition to plutonium dosimetry in human bone.

The surface deposit thickness was found to be less than 5 μm and is thus similar in magnitude to that found in Cases 40-010 and 40-015. Although only three cases have been studied and none has been widely sampled for surface thickness measurements, we believe that thin surface deposits are a universal rule for humans.

Conclusions

In summary, our conclusions are that:

(1) In the absence of bone remodeling, concentrations are not greatly different on endosteal, Haversian canal and periosteal surfaces of long bone midshafts, 17 months after injection.

(2) Endosteal surfaces in the axial skeleton show higher concentrations than surfaces in the appendicular skeleton at 15 and 17 months post-injection.

(3) The thickness of volume deposits formed by appositional growth exceeds the alpha particle range. Thus, the deposits are "infinitely thick" for dosimetric purposes and existing surface cells are shielded from intense buried surface deposits.

(4) Surface deposits are so thin that, for purposes of dose calculation, they can be considered to have zero thickness.

(5) The secondary surface deposits are of considerable dosimetric significance, even when the plutonium is primarily deposited in the volume of bone.

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