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ESTIMATION OF THE TURNOVER EQUATION OF STRONTIUM-90 FOR HUMAN BONES

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Evaluation of radiation exposure from Sr^{90} needs to be based upon knowledge of its distribution and residence time in bone. In adult animals, a significant portion of administered radioisotopes of the alkaline earths is distributed quite uniformly throughout the compact bone, the diffuse component. Regions of high concentration of radioactivity can also be found (10 to 12 times that of the diffuse background) in sites of active bone mineral deposition, the "hot spots".[1-4] It is understood that any determination of gross skeletal Sr^{90} turnover represents the sum of the Sr^{90} turnover in the individual bones and in the different regions of the same bone.

Information on bone mineral turnover in human beings is lacking, and to evaluate the probable equation of Sr^{90} turnover in man the turnover values are being measured in rhesus monkeys. Much of the published literature on calcium and strontium metabolism has been derived from experiments with laboratory rodents whose skeletal growth patterns and microscopic skeletal anatomy are very different from other mammalian species. In order to relate this information to the monkey data similar turnover studies have been performed in adult rats using the double-labeling technique.

METHODS

Eight rhesus monkeys of both sexes 2.75 to 3.2 years old were given intravenous injections of Sr^{90} complexed with sodium citrate (five also received 135 μC of Ca^{45}). After injection the animals were kept in metabolism cages for periodic collection of excreta. Two animals have been followed for 4 years, three for 1 year, and three for 1 month. Seventy-five female rats (two age groups, 65 days and 110 days old) were given simultaneous intramuscular injections of 0.5 μC of Sr^{90} and 1 to 10 μC of Ca^{45} in sodium citrate solution. These were estimated to be the lowest dosages that would allow accurate counting of the excreta 8 to 16 months after administration. Excretions were collected continuously from the day of injection, and groups of six to

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eight rats have been autopsied periodically for measurement of skeletal retention.

Samples were prepared by ashing followed by solution of the residue in 0.5 M HNO_3. Duplicate aliquots were evaporated on glass counting plates according to previously described methods[5]. Calcium-45 and Sr^{90} activities were determined by differential counting with a 70 mg/cm^2 Al absorber using a thin-window G-M counter. Appropriate corrections were made for Ca^{45} and Sr^{90}-Y^{90} self absorption and for Sr^{90}-Y^{90} back scattering and absorption in the Al shield. When the counting rate of a 10 mg/cm^2 excreta sample approached 10 times the background count, a correction for K^{40} content of the sample was applied. A total probable error of ±10% was estimated for injection volumes, sample collection and handling, self absorption, mass absorption, K^{40} corrections, and for counting statistics. Total recoveries of Ca^{45} ranged from 90% to 105%, and of Sr^{90} from 101% to 110%.

RESULTS

The turnover equations obtained for Ca^{45} and Sr^{90} in adult rats and for Sr^{90} in monkeys are as follows:

Percent Administered Dose Per Organ in Skeletal Parts

Ca^{45} rat - 65 days old

Vertebrae	0.4% exp (-0.693d/3) + 3% exp (-0.593d/180)
Mandible	3.5% exp (-0.693d/330)
Long bones	0.9% exp (-0.693d/1) + 1.8% exp (-0.693d/12) + 4.5% exp (-0.693d/450)
Whole skeleton	4.4% exp (-0.693d/2) + 6% exp (-0.693d/6) + 67% exp (-0.693d/570)

110 days old

Skull cap	2.88% exp (-0.693d/580)
Long bones	0.85% exp (-0.693d/0.8) + 1.65% exp (-0.693d/9) + 3.82% exp (-0.693d/520)
Whole skeleton	24.5% exp (-0.693d/0.8) + 22% exp (-0.693d/28) + 53.5% exp (-0.693d/560)

Sr^{90} rat - 65 days old

Vertebrae	0.8% exp (-0.693d/13) + 1.83% exp (-0.693d/180)
Mandible	0.4% exp (-0.693d/16) + 2.4% exp (-0.693d/330)
Long bones	1.3% exp (-0.693d/3) + 0.9% exp (-0.693d/15) + 3.0% exp (-0.693d/450)
Whole skeleton	7% exp (-0.693d/2) + 12% exp (-0.693d/12) + 43% exp (-0.693d/570)

110 days old

Skull cap	0.39%/g exp (-0.693d/2.5) + 0.4%/g exp (-0.693d/5) + 1.73%/g exp (-0.693d/600)
Long bones	1.4% exp (-0.693d/0.75) + 1.85% exp (-0.693d/10) + 2.12% exp (-0.693d/510)
Whole skeleton	24% exp (-0.693d/0.6) + 24% exp (-0.693d/0.9) + 21% exp (-0.693d/12) + 31% exp (-0.693d/575)

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Sr^{90} Monkey - 3 years old

$$47.5\% \exp(-0.693d/0.75) + 10\% \exp(-0.693d/9.5) + 9\% \exp(-0.693d/48) + 27\% \exp(-0.693d/980)$$

It should be pointed out that these turnover equations were based on relatively short observation periods, 4 years for a small number of monkeys and 8 months for the rats. It is possible that as the observation period is extended pathological skeletal changes from the radiation exposure* along with approaching senility may contribute additional slower components which will alter the turnover rates and compartment sizes given here.

DISCUSSION

Strikingly similar skeletal elimination rates of Sr^{90} and Ca^{45} were observed in the rat, especially in comparisons based upon whole-skeleton values. In the rat there appear to be different characteristics of bone mineral turnover in the flat and in the long bones which can be reasonably related to the differential growth properties of the individual bones. It is apparent, however, that a gross similarity exists between the separate bones and the entire skeleton.

A remarkable similarity was found when the Sr^{90}-turnover equations for the rat and the monkey were compared, and this similarity suggests that the turnover equation for the monkey may be a reasonable estimation of turnover of Sr^{90} in the human skeleton. One may then estimate the fractions of adult human bone that equilibrate with Sr^{90} and the rate at which such equilibration occurs.

These are:

0.13% of bone turnover with a half time of .75 days
0.35% of bone turnover with a half time of 9.5 days
1.75% of bone turnover with a half time of 48 days
97.7% of bone turnover with a half time of 980 days

The average cumulative radiation in bone following acute exposure to Sr^{90} is largely determined in that portion of the skeleton in which turnover rate is slowest; in this case 98% of the bone accumulates 27% of the administered Sr^{90} and subsequently eliminates it with a half time of 980 days. It is noted that for man an average Sr^{90} turnover in bone of about 1000 days would give a reasonable agreement with the Sr^{90} content of human bone as reported by Libby and others over the period from 1953 to 1957.[6]

* The radiation exposure accumulated by the skeleton of the 110-day old rat during the first 8 months was estimated from the retention equations. Assuming a uniform distribution of the radioisotopes in 27g of bone, 0.5μC of Sr^{90} and 10μC of Ca^{45} will deliver 63 rad and 130 rad, respectively (190 rad for doubly-labeled animals). Sixteen months after injection the accumulated exposure is estimated at 280 rad. "Hot spots" may have received as much as 1400 rad (1/2 uniform dose × 10).

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A human being exposed initially to a bone burden of 1 mμC of Sr^{90} (assuming uniform distribution in a bone mass of 7000 g) would have the following retention of Sr^{90} and radiation exposure (if he were not subsequently re-exposed to Sr^{90}).

Time (yr)	Sr^{90} (mμC)	Dose (mr/yr)	Accumulated exposure (mr)
0 (initial exposure)	1	2.8	0
2.7	0.5	2.0	5.4
5.4	0.25	1.0	8.1
8.1	0.13	0.5	9.5
-	0	0	10.8

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