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Evidence of High Natural Radiation Doses in Certain Mid-Water Oceanic Organisms

Abstract. *Concentrations of the naturally occurring radioactive nuclide polonium-210 were determined in mid-water crustaceans and fish from depths to 1500 meters. Unusually high levels were found in certain categories of organisms, indicating that these organisms were exposed to a particularly high natural radiation dose. The results have implications in terms of possible radiation effects, as a baseline against which artificial radioactive nuclides can be compared, and as a potential technique for studying the feeding behavior of mid-water organisms.*

Radon emanated from the earth's crust decays in the atmosphere and gives rise to a natural radioactive fallout of its descendants ^{210}Pb, ^{210}Bi, and the alpha-particle emitter ^{210}Po (*1*). This fallout is deposited over the oceans as well as the continents, and ^{210}Po is particularly concentrated by most marine organisms (*2*). As a result, the natural radiation dose received by such organisms is usually substantially higher than that received by man. The published data for ^{210}Po in marine organisms were reviewed in 1974 (*2*) and expanded in subsequent publications (*3–8*). Almost all of these data were obtained from animals collected in surface or shallow waters; very limited information has been available concerning material from greater depths in the ocean (*7, 8*).

We report here ^{210}Po concentrations in several crustaceans and fish from depths to 1500 m and in a few deep benthic crustaceans. The extremely high concentrations we found in some cases imply that certain categories of marine animals are exposed to a natural radiation dose which is, to our knowledge, the highest yet reported. These data are of interest for several reasons. (i) The implications of the exposure of a section of the biosphere to a particularly high natural radiation dose over the entire period of biological evolution could be of fundamental importance. (ii) Low-level radioactive waste is already being dumped in the oceans on a small scale, and subseabed disposal in deep ocean sediments has been discussed as a high-level waste disposal option (*9*). The possible hazards arising from the uptake of artificial radioelements into marine organisms will have to be assessed carefully, and such assessment will be difficult because of the lack of data on radiation effects at the low activity levels likely to be encountered. Comparison with the natural radiation dose seems inevitable, and since ^{210}Po provides more than 90 percent of this dose to most marine organisms (*2*) it is important that our knowledge of ^{210}Po concentrations in mid-water and deep-sea organisms be as complete as possible. (iii) The involvement of ^{210}Po in the oceanic biological cycle is extensive, and the nuclide has been shown to be a useful tracer of marine biological processes (*6, 8*). The data reported here support our earlier suggestion (*6, 8*) that ^{210}Po studies can provide useful information about the feeding behavior of certain organisms.

Polonium-210 determinations were made by the standard technique of acid digestion, spontaneous deposition of ^{210}Po from an acid solution onto a silver disk, and counting of the ^{210}Po alpha radioactivity on the disk with ZnS(Ag) scintillation phosphors (*8, 10–12*). The technique is simple, efficient, and highly reproducible; experience with several hundred marine organism samples over a period of many years has shown that our deposition efficiency for ^{210}Po is 98 ± 2 percent. For an individual sample, the major contribution to the error is the statistical counting error. Most of our errors are between 5 and 10 percent. The results of more than 70 measurements on whole animals are reported in Table 1. Almost all the samples were provided by colleagues in other institutions (*13*).

The data in Table 1 are to be compared with published data for ^{210}Po in the same types of organisms from surface and shallow waters. Our data for amphipods, copepods, euphausiids, and mysiids show ^{210}Po concentrations that are generally comparable with those reported for surface samples; the significance of any differences cannot be established until more data are available. A typical value for ^{210}Po in entire fish, mostly from surface waters, has been given as 1.5 pCi/g (*2*); the range of published values, covering more than 50 samples, is from 0.3 to 26 pCi/g (*2*). (All values are given on the basis of dry weight.) Only our Gonostomatidae are at the typical level; the other three families have medians at or beyond the upper end of the range for surface fish. Pentreath *et al.* (*7*) reported that ^{210}Po concentrations in organs and tissues from fish (Alepocephalidae, Gadidae, Macrouridae, and Squalidae) caught between 500 and 1250 m were generally similar to those observed for surface fish. Our data indicate that certain categories of mid-water fish contain consistently high levels of ^{210}Po. On the basis of four species of shrimp caught below 600 m, we suggested (*8*) that mid-water shrimp are significantly higher in ^{210}Po than those from surface waters. Nine more species are represented in the shrimp from 610 to 1500 m in Table 1, and Table 2 shows the ^{210}Po concentration for each of the 13 species from below 600 m. In the mid-water penaeids ^{210}Po ranges from 25 to 117 pCi/g with a median of 43 pCi/g; in eight species of pelagic penaeids from surface waters (*8*) the range was 6.6 to 23.6 pCi/g with a median of 15.7 pCi/g. Of the mid-water penaeids those from the genera *Gennadas* and *Bentheogennema* all have higher ^{210}Po levels than those from the genus *Sergestes*. The same feature is observed in the penaeids from 50 to 760 m (not listed in Table 2): a single *Gennadas* species has a ^{210}Po concentration of 98 pCi/g, while four species of *Sergestes* have 11 to 33 pCi/g. The mid-water carids (9 to 21 pCi/g; median, 14 pCi/g) also have higher ^{210}Po levels than five carid species from surface waters (*8*) (1.3 to 10.4 pCi/g; median, 5.2 pCi/g). The penaeid-carid difference discussed previously (*8*) is again observed; penaeids, which are more primitive in the evolutionary sense, have higher ^{210}Po levels than carids at all three depths (Table 1). The two bathypelagic shrimp samples from 4000 m have ^{210}Po levels typical of surface rather than of mid-water shrimp; more measurements are needed to determine whether this is generally the case.

The following categories of marine organisms from the mid-water region (600 to 1500 m) appear to have consistently high whole-animal ^{210}Po contents: carid shrimp, ~ 14 pCi/g; Sternoptychidae and Myctophidae fish, ~ 25 pCi/g; *Sergestes* penaeid shrimp, ~ 32 pCi/g; and penaeid shrimp from *Gennadas* and *Bentheogennema*, ~ 84 pCi/g. Polonium-210 is nonuniformly distributed in the tissues of marine organisms, with particularly high levels in the hepatopancreas of crustaceans and cephalopods (*2, 6, 8*) and the liver of fish (*2, 7*). We dissected out the hepatopancreas from ten mid-water samples, five comprising penaeid shrimp and five comprising carid shrimp, and measured median ^{210}Po concentrations of 584 and 128 pCi/g in penaeid and carid hepatopancreas, respectively. The highest ^{210}Po concentration that we measured was found in a sample of five individuals of *Gennadas valens* taken between 895 and 1010 m in the mid-Atlantic: 138 $\pm$ 8 pCi/g in the whole animals and 856 $\pm$ 51 pCi/g in the hepatopancreas. These are, to our knowledge, the highest natural ^{210}Po levels recorded to date in biological organisms. The wet/dry ratio in the hepatopancreas is about 3; using this value and the median concentration of 584 pCi/g in the mid-water penaeid hepatopancreas and assuming a relative biological efficiency of 10 for ^{210}Po alpha particles (*14*), we calculate a radiation dose from ^{210}Po to the hepatopancreas of ~ 195 rem/year. If we used the ICRP recommendation (*15*) of 20 for the relative biological efficiency we would obtain twice this dose. Such doses are very large by human standards. The dose received by the lung, the human organ which is generally considered to receive the highest total natural radiation dose on the average, is almost three orders of magnitude lower at 0.4 rem/year (*16*). Man is, however, among the most radiosensitive organisms (*17*), and laboratory studies indicate that marine invertebrates are much less so (*18*). It is unlikely that doses of about 100 rem/year will affect the hepatopancreas to the same extent as a human tissue, but the possibility that such effects might be observed should not be overlooked. Comparative cytological studies of the hepatopancreas of shrimp from different natural radiation dose domains are indicated. Moreover, it would be of interest to know whether exposure of organisms to high natural radiation doses on the evolutionary time scale would favor the development of radiation resistance and whether a wide range in the natural radiation regime implies a wide range of radiosensitivity. The importance of research on the radiosensitivity of marine ecosystems was pointed out in the RIME report (*17*) a decade ago. Detailed studies relating ^{210}Po levels to different niches of marine ecosystems might throw some light on this difficult topic.

Our data support the conclusions of Pentreath *et al.* (*7*) that the natural radiation regime for organisms in the deep ocean is not likely to be any lower than that for organisms in coastal water and is also not likely to be constant. We have found several types of mid-water organisms that are exposed to high natural radiation, but have found no evidence of a type that is exposed to particularly low natural radiation.

There is evidence (*4, 6, 8*) that the main immediate source of ^{210}Po in marine organisms is the food they consume, and the variations in ^{210}Po between different kinds of shrimp have been related to differences in feeding habits. The penaeid-carid difference may reflect a difference in the way the prey is consumed; penaeids may lose less ^{210}Po since they tend to swallow food items whole, whereas carids tend to break up food in the mouth parts outside the body (*6, 8*). It is possible that ^{210}Po measurements can throw light on the feeding behavior of fish as well; those high in ^{210}Po may be detritivores feeding on fecal pellets or organic particulates that are rich in ^{210}Po (*19–22*) or predators feeding on ^{210}Po-

Table 1. Polonium-210 concentrations in mid-water and deep benthic crustaceans and fish. All measurements were made on whole animals; in most cases samples comprised several individuals. Mid-Atlantic samples were from the region 31° to 35°N, 28° to 35°W; Central Pacific samples were from close to 31°N, 159°W. Most samples were collected in vertical trawls ranging over several hundred meters in depth; where only one figure is cited for depth, samples were from close to the ocean floor.

Category	Origin	Depth (m)	Number of samples	^{210}Po (pCi/g, dry) Range	Median
Shrimp					
Penaeid	Mid-Atlantic	610–1500	9	12–138	49
Penaeid	Mid-Atlantic	50–760	7	11–98	26
Penaeid	Hudson Canyon	4000	1	18	18
Carid	Mid-Atlantic	610–1500	10	9–21	14
Carid	Mid-Atlantic	50–760	5	4–22	8
Carid	Hudson Canyon	4000	1	1.4	1.4
Fish					
Gonostomatidae	Mid-Atlantic	610–1500	2	0.5–1.4	1.0
Gonostomatidae	Mid-Atlantic	50–760	1	1.4	1.4
Melamphaeidae	Mid-Atlantic	610–1500	2	3–74	39
Myctophidae and Sternoptychidae	Mid-Atlantic	610–1500	3	11–53	25
Myctophidae and Sternoptychidae	Mid-Atlantic	50–760	3	22–30	24
Amphipods	Central Pacific	6000	9	3–24	8
Amphipods	Rockall Trench	0–2000	2	18–19	19
Copepods	Mid-Atlantic	610–1500	2	9–13	11
Mysiids	Mid-Atlantic	610–1500	5	1.0–15	1.4
Euphausiids	Mid-Atlantic	610–1500	6	0.3–5.3	1.9

Table 2. Polonium-210 in whole shrimp caught below 600 m. In most cases samples comprised several individuals.

Superfamily and species	Origin	Depth (m)	Number of samples	Median ^{210}Po (pCi/g, dry)
Penaeidae				
Gennadas valens	Mid-Atlantic	610–1500	3	117
Bentheogennema intermedia	Mid-Atlantic	610–1500	1	84
Gennadas elegans	Mediterranean	600–1200	2	45
Sergestes sp.	Natal	800–1300	1	43
Sergestes prehensilis	Natal	800–1300	1	39
Sergestes henseni	Mid-Atlantic	610–1500	2	25
Sergestes robustus	Mid-Atlantic	610–1500	1	25
Caridae				
Systellaspis debilis	Mid-Atlantic	610–1500	1	21
Pasiphaea sp.	Mid-Atlantic	610–1500	1	15
Acanthephyra purpurea	Mid-Atlantic	610–1500	6	14
Acanthephyra quadrispinoza	Natal	800–1300	1	14
Systellaspis debilis	Natal	800–1300	1	14
Acanthephyra pelagica	Mid-Atlantic	610–1500	1	11
Acanthephyra stylorostratis	Mid-Atlantic	610–1500	1	9

rich prey [for instance, a mid-water shrimp, or selective feeding on its hepatopancreas (8)]. The low ^{210}Po family, the Gonostomatidae, must have a completely different, low ^{210}Po diet—copepods, perhaps. Sorting of fish according to genus and size before measurement of ^{210}Po could provide information on feeding behavior complementing that obtained by the standard technique of stomach content examination.

Finally, the measurement technique used also gives data for ^{210}Pb, the grandparent of ^{210}Po. These data are less reliable than those for ^{210}Po; levels of ^{210}Pb in marine organisms are much lower (2, 6, 8) and errors are much larger. In some of our mid-water shrimp and fish samples, a conservative assessment of errors led us to conclude that ^{210}Pb concentrations were frequently more than 1 pCi/g dry, a level rarely observed in surface shrimp and fish. In four samples of bathypelagic carid shrimp we found ^{210}Pb concentrations ranging from 0.09 to 1.17 pCi/g and in one penaeid 0.65 pCi/g; for surface carids and penaeids median ^{210}Pb concentrations of 0.04 and 0.20 pCi/g, respectively, have been reported (8). In benthic amphipods from the central Pacific ^{210}Pb ranged from 0.6 to 5.3 pCi/g (median, 1.1 pCi/g), while in surface amphipods [(23) and our unpublished results] the range was 0.2 to 1.5 pCi/g (median, 0.5 pCi/g). If confirmed, higher ^{210}Pb levels in mid-water and deep sea organisms could have implications for the overall geochemical balance of ^{210}Pb in the water column. In most cases where ^{210}Pb was measured there was a tendency for the ^{210}Po/^{210}Pb activity ratio to be lower than in the corresponding surface animals. The ^{210}Po/^{210}Pb ratio ranges over more than two orders of magnitude in oceanographic materials. Fecal pellets and oceanic particulates are rich in ^{210}Po and have a ^{210}Po/^{210}Pb ratio of about 2 (19–22); shrimp hepatopancreas have this ratio approaching 100 (6, 8). Measurements of ^{210}Po/^{210}Pb ratios in mid-water organisms might aid the assessment of the relative contribution of detritus to the animals' diet.

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Evidence That Glucose "Marks" β Cells Resulting in Preferential Release of Newly Synthesized Insulin

Abstract. *Studies of isolated islets labeled with radioactive leucine show that glucose at a critical time "marks" islets in such a way as to cause preferential release of newly synthesized insulin. The preferential release of insulin from marked islets is relatively independent of subsequent secretagogues or rates of insulin secretion. Previous kinetic studies have indicated that the critical time at which marking occurs is after proinsulin biosynthesis but before the secretory event. Thus, secretory cells may regulate the diversion of newly synthesized material for immediate release as it is approaching or transiting the Golgi apparatus.*

Investigators at several laboratories, including our own, have concluded that newly synthesized insulin is secreted preferentially from glucose-stimulated pancreatic slices (1) or islets (2–9). This conclusion was based on results from experiments with radioactively labeled islets that showed that secreted insulin has a higher specific activity than the average cellular insulin and that radioactive insulin is secreted at a higher fractional rate than immunoreactive insulin (IRI). The results were the same whether islets were selected from the entire pancreas or only from either the dorsal or ventral regions (9), which are known to contain islets that differ from each other in their hormonal storage and secretion characteristics (10). Similar observations of nonrandom secretion also have been made for placental lactogen (11), prolactin (12), parathyroid hormone (13), salivary amylase (14), pancreatic amylase (15), gonadotropin (16), vasopressin (17), thyroglobulin (18), and acetyl choline (19). However, it has not been established whether preferential secretion reflects an intrinsic process of secretory cells that can be regulated in response to physiologic conditions. In the study reported here we show that the same newly synthesized insulin can be secreted either preferentially or near-randomly. The determining event precedes secretion, is glucose-sensitive, and occurs during what we call the "marking" period.

The effect of glucose during the early period of a pulse-labeling experiment on the specific activity of subsequently secreted insulin is shown in Fig. 1. Groups of islets were identically labeled with [^{3}H]leucine, exposed to either 20 or 2 m*M* glucose from minutes 15 to 90 (the marking period), then similarly incubated again in a high concentration of glucose. Noncumulative samples of secreted insulin were collected for two consecutive 20-minute observation periods (windows) during this later period. Secreted and islet insulin were purified separately without carrier by a sequence