Abstract. We report here radiocarbon measurements of monkey eye lens nucleus proteins and a narwhal tusk, biological tissues which have sampled the bomb radiocarbon signal in different ways. The results confirm the metabolic inertness of eye lens nucleus proteins and demonstrate the feasibility of measuring radiocarbon in small samples of biological tissue using accelerator mass spectrometry (AMS). The narwhal tusk provides a unique record of the radiocarbon activity in Arctic Ocean waters over most of the 20th century.

Introduction

The detonation of thermonuclear weapons in the atmosphere during the 1950s and early 1960s nearly doubled the radiocarbon (14C) activity of tropospheric carbon dioxide by 1964 [Nydal and Løvseth, 1983]. Although this bomb radiocarbon signal has steadily decreased since the ratification of the limited atmospheric test ban treaty in October 1963, the current radiocarbon activity of atmospheric carbon still exceeds pre-bomb levels by about 15-20% [Levin et al., 1985]. The radiocarbon levels of dissolved inorganic carbon (DIC) in ocean surface waters also increased, but more slowly and to a much smaller extent [Broecker et al., 1985]. Mixing with subsurface waters acted to dampen the bomb radiocarbon signal in surface waters, and the long residence time of radiocarbon in the atmosphere delayed the peak maximum in the ocean nearly 10 years [Druffel and Suess, 1983]. Numerous studies have utilized the radiocarbon "spike" derived from nuclear weapons testing to investigate various oceanographic [Broecker et al., 1985; Druffel and Suess, 1983], geochemical [Hedges et al., 1986], and biological [Mok et al., 1986] processes. We have investigated the bomb radiocarbon signal in metabolically stable tissues of a terrestrial and a marine mammal in order to assess the utilization of the bomb "spike" as a tool for studying protein turnover rates and for providing radiocarbon records in regions where few or no previous radiocarbon measurements are available.

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provides independent verification that the lens nucleus protein A4C value of -6±2% measured in the monkey born in 1950.

In contrast to both the monkey lens analysis (Fig. 1) and the record in corals, the bomb signal in the narwhal tusk is very weak. In the layers deposited before the major nuclear explosions in the late 1950s and early 1960s, the radiocarbon activities ranged from -10 to -18%. Similarly depleted radiocarbon activities have been found in the tissues of other prebomb polar marine mammals and birds [Tauber, 1979; Mabin, 1986]. During and after the interval of atmospheric weapons testing, A4C values in the narwhal tusk rose to a maximum of -2.0% by the late 1960s, and then decreased to values nearly as low as those recorded in prebomb layers. In comparison, the bomb signal in corals was more pronounced and has declined only slightly since reaching a maximum value around 1970. Thus, radiocarbon in Arctic Ocean waters as recorded in the narwhal tusk was less affected by bomb radiocarbon than other oceanic waters even though the largest atmospheric detonations were carried out in the Arctic regions of the USSR [Carter and Moghissi, 1977]. Present day subsurface (>200 m) waters in the Canadian Arctic Ocean have radiocarbon levels which range from -5.0 to -15.0%, while surface waters range from -2.5 to +3.0% [Ostlund et al., 1987]. Deep convective mixing in the Arctic Ocean serves to dilute the radiocarbon in surface waters to a much larger extent than at lower latitudes (e.g., as recorded in corals). Since there are no data on radiocarbon in Arctic Ocean waters prior to 1979 [Ostlund et al., 1987], the narwhal tusk provides a unique time history of Arctic Ocean radiocarbon values over the last five decades. Unfortunately, due to the migratory behavior and feeding habits of the narwhal, this record cannot be interpreted solely as a reflection of Arctic Ocean mixing processing in one localized area, i.e., the Baffin Island region where the narwhal was killed. Similar studies using metabolically stable tissues from other cetaceans should provide important long-term records of radiocarbon activities in various oceanic areas.

The monkey lens results suggest that the artificial bomb radiocarbon signal may have a variety of applications in mammalian biology. Using the radiocarbon activities in the ocular lens nucleus and other metabolically stable proteins such as dentin, it should be possible to determine whether an
animal was born prior to the period of bomb radiocarbon production. This technique could be valuable in establishing the minimum age of animals which are difficult to age by other biochronological methods such as dentinal growth counts or aspartic acid racemization. It should be possible to extend this bomb radiocarbon based aging method to other species such as non-aquatic birds and reptiles. In addition the radiocarbon activity in proteins with poorly known turnover rates could be used to evaluate whether they are inert or metabolically active. For example, further studies of the radiocarbon activities in a lens cross-section would help define the region where there is active protein synthesis. This type of analysis could easily be extended to the proteins and other organic components in bone, skin, and the brain.

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References

Bada, J.L. and S. Brown, In vivo racemization in teeth and the ocular lens nucleus, in Behavior and Pathology of Aging in Rhesus Monkeys, Monographs in Primatology Vol. 6, edited by R.T. Davis and C.W. Leathers, pp. 91-100, Alan R. Liss, New York, 1985.

Bada, J.L., E. Mitchell, and B. Kemper, Aspartic acid racemization in narwhal teeth, Nature, 303, 418-420, 1983.

Batten, R.J. et al., A review of the operation of the Oxford radiocarbon accelerator unit, Radiocarbon, 28, 177-183, 1986.

Broecker, W.F., T.-H. Peng, G. Ostlund, and M. Suvi, The distribution of bomb radiocarbon in the ocean, J. Geophys. Res., 90, 6953-6970, 1985.

Carter, M.W. and A.A. Moghissi, Three decades of nuclear testing, Health Physics, 33, 55-71, 1977.

Druffel, E.M. and H.E. Suess, On the radiocarbon record in banded corals: exchange parameters and net transport of $^{14}$CO$_2$ between atmosphere and surface waters, J. Geophys. Res., 88 (No. C2), 1271-1280, 1983.

Harding, J.J., Nonenzymatic covalent posttranslational modification of proteins in vivo, Adv. Protein Chem., 37, 247-334, 1985.

Hedges, J.I., et al., Organic carbon-14 in the Amazon River system, Science, 231, 1129-1131, 1986.

Levin, I., B. Kemper, H. Schoch-Fisher, M. Brans, M. Munich, D. Berdan, J.C. Veogel, and K.O. Munnich, 15 years of tropospheric $^{14}$C observations in central Europe, Radiocarbon, 27, 1-19, 1985.

Mahin, M.C.G., Radiocarbon dating of 'Heroic Era' penguin and seal remains from Antarctica, Geol. Soc. Am. Abst. with Programs, 18 (No. 6), 678, 1986.

Mok, H.Y.L., E.R.M. Druffel, and W.M. Rampone, Chronology of cholelithiasis; dating gallstones from atmospheric radiocarbon produced by nuclear bomb explosions, New Engl. J. Med., 314, 1075-1077, 1986.

Nydal, R. and K. LoVeth, Tracing $^{14}$C in the atmosphere 1962-1980, J. Geophys. Res., 88, 3621-3642, 1983.

Ostlund, H.G., G. Possnert, and J.H. Swift, Ventilation rate of the Deep Arctic Ocean from carbon 14 data, J. Geophys. Res., 92 (No. C4), 3769-3777, 1987.

Ozaki, L., P. Jap, and H. Bloemendal, Protein synthesis in bovine and human nuclear fiber cells, Exp. Eye Res., 41, 569-575, 1985.

Tauber, H., $^{14}$C activity of Arctic marine mammals, in Radiocarbon Dating, edited by R. Berger and H.E. Suess, pp. 447-452, University of California Press, Berkeley, Los Angeles, London, 1979.

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