THE EVOLUTION OF THE EARTH'S BACKGROUND RADIATION LEVEL OVER GEOLOGIC TIME

P. Andrew Karam CHP and Stephen A. Leslie Ph.D.
Department of Geological Sciences, The Ohio State University, Columbus, U.S.A

INTRODUCTION

The earth currently has a background gamma radiation level of 0.28 mSv/yr due to radionuclides such as U, Th, Ra, and ^{40}K (1), and humans are exposed to approximately 0.40 mSv/yr from ^{40}K in their bodies. An additional dose of 2.90 mSv/yr is derived from radon (2.0 mSv/yr), building materials (0.28 mSv/yr), cosmic radiation (0.27 mSv/yr) and various anthropogenic sources (1). Owing to the low penetrating power of alpha radiation, radon does not expose the whole body to ionizing radiation. Of the natural sources of gamma radiation the nuclides K, U+progeny, Th+progeny are Large Ion Lithophiles (LILs) and are preferentially partitioned into the continental crust. Since the amount of crust has increased with time, LIL abundance at the earth's surface has increased over geologic time. These elements are all radioactive with half-lives of less than the age of the Earth (except for ^{232}Th), and are now present in lower activity concentrations in the continental crust than at any time in the geologic past.

Prokaryotic life is thought to have evolved between 3.5 and 4 billion years ago (Ga), giving rise to eukaryotic life as early as 2.1 Ga (2) . It is further thought that primitive organisms resembled current life in terms of radiation repair mechanisms, potassium content, and basic biochemistry, based on remarkable similarities in basic chemical compositions of modern primitive and advanced life forms (3).

This paper examines the evolution of the background radiation field in which primitive organisms evolved in terms of internal dose (from internal ^{40}K) and external geologic dose (from gamma emitters in the crust of the earth), and how this may relate to dose-response in modern organisms.

GEOLOGIC AND INTERNAL DOSE

Crustal evolution was not uniform throughout time. Taylor and McClennan (4) suggested that the major epoch of crust formation occurred between 2.8 and 2.6 Ga. The oldest crust known dates from about 3.8 Ga. Ocean chemistry at this time is suggested to be similar to that of today's oceans (5).

LILs are partitioned into the molten phase of magma and discharged into the crust in magma intrusions or erupted as lava. These elements concurrently decay towards stable end products. Since the surface gamma radiation field from these elements is proportional to their activity concentration (6), competing mechanisms determine surface radiation levels from geologic sources (Fig. 1). Using Taylor and McClennan's (4) model for crust formation and assuming that LIL concentration was equal to the percentage of crust formed (i.e. LILs had one half of their current concentrations when the crust was 50% formed) then, at the time that life evolved, surface gamma radiation levels due to contact with the continental crust were similar to those at present, rising to approximately twice current levels at the time that eukaryotic life evolved. Therefore, life would have been exposed to up to four times current levels of external gamma radiation due to contact with the continental crust. In addition, based on a current ^{40}K concentration in seawater of 11 Bq/gm (7), organisms in the water column at that time would have received comparable doses from ^{40}K beta and gamma radiation.

Potassium is essential to life and is not evenly distributed in organisms. Most cells selectively maintain a K concentration approximately one order of magnitude greater than that found in extracellular fluids (8,9). Average K content in human muscle is approximately 155 moles/m^3, compared to an average interstitial fluid content of 4 mol/m^3 (9). Single-celled organisms appear to maintain a similar concentration factor, most at higher internal concentrations. For example, *Acetabularia mediterranea* (a single cell plant) contains 400 mol/m^3 K in its cytoplasm, 355 mol/m^3 in vacuoles, and 10 mol/m^3 in external solution (9). Our model uses the K content of human muscle, which appears to be a conservative estimate, as the basis for internal dose estimates through geologic time.

Radiological dose is measured in terms of energy deposited per unit of mass. Although a single-celled organism has much less potassium than a human, it also has far less mass. Therefore, we assume that the dose due to internal potassium activity remains constant at all scales. Many single-celled organisms are smaller than the mean free path of photons or beta particles in the cell. However, many early organisms were colonial (stromatolites, algal mats, etc). We assume that the thickness of these colonies is greater than the stopping distance of ^{40}K betas in water (approximately 0.7 cm) and that, as a result, the beta decay energy is deposited in the colony with each member receiving an approximately equal share.

Humans currently receive approximately 0.40 mSv/yr from internal ^{40}K. The majority of this dose is due to the 1.33 MeV beta decay (~89%) with the balance resulting from the 1.46 MeV gamma (~11%). The specific activity of potassium currently is 31.6 Bq/gm. Three half-lives ago (approximately 4 Ga), K had a specific activity of 253 Bq/gm giving a yearly dose of 3.20 mSv.

There is currently a component of dissolved uranium to which we are exposed via drinking water. The short range of an alpha particle results in the deposition of a high percentage of its energy within the cell. However, uranium is insoluble under the reducing conditions which existed during the Archaean and is not likely to have contributed much dose to organisms at this time.

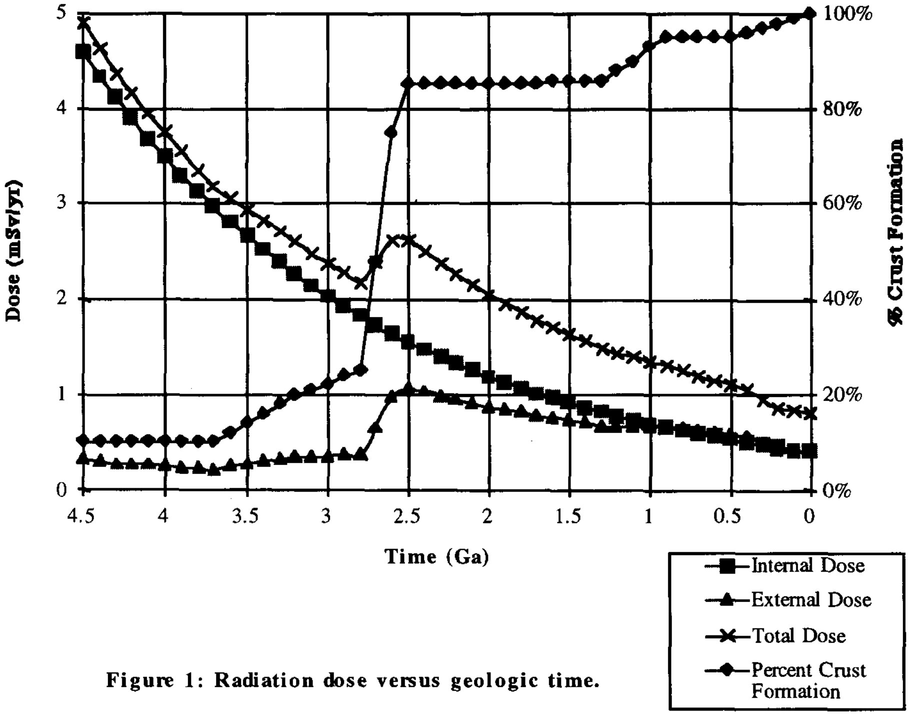

Figure 1: Radiation dose versus geologic time.

ULTRAVIOLET RADIATION

Kasting and others suggested (10) ozone did not exist during the Archaean due to a lack of free oxygen and could not have shielded the earth from ionizing UV radiation. The portion of the UV spectrum most likely to penetrate to the surface is the most energetic (10), UVC (200-280 nm). A high flux of UVC is thought to have sterilized the surface of the earth until a protective ozone layer developed. In addition, penetration of UVC through shallow pools of water or into shallow portions of the ocean may have further increased the ionizing radiation dose to organisms. During the Archaean, solar luminosity was approximately 70% present levels (11). This corresponds to a lower solar surface temperature, giving a UVC flux of 50-70% present levels. Therefore, the UVC flux reaching the earth at this point in time was much less than at present.

While free oxygen did not exist at this time, the earth's atmosphere was considerably thicker than at present, consisting of up to 10 bars of CO_2 with nitrogen, water vapor, nitrous oxides, and trace gases (11). Due to high CO_2 levels, mean surface temperatures were likely between 20° and 50° C, with a corresponding increase in water content and cloud cover (11). In addition, increased volcanic activity would have increased atmospheric loading of aerosols, including sulfur compounds, many of which absorb strongly in the ultraviolet (12). Because of this we feel that, while UVC levels may have been higher prior to formation of the ozone layer, they would not have added significantly to the radiation levels to which early organisms were exposed. We do not know if life evolved at the surface, in the sediments, in shallow water, or in deep water. We do know, however, that the presence of life today indicates that life evolved in an area in which UV radiation was not lethal to it.

DISCUSSION

It seems likely that life was exposed to much higher radiation levels throughout much of its history than exist at present. We estimate the dose due to internal ^{40}K activity to have ranged from four to eight times that at present throughout the time that only prokaryotic and eukaryotic life existed. At the time that metazoan life arose (0.7-1.0 Ga), internal radiation dose was approximately twice that at present.

The dose from geologic materials has changed in the past, although not as monotonically as has internal dose. As the continents formed, the dose from geologic materials increased to four times what we now experience, decreasing due to radioactive decay and, lately, due to the formation of organic soils.

Mutation rates are proportional to radiation dose and dose rate (13). If radiation levels have changed over time, then mutation rates must also have changed over time. The molecular clock, then, may have run faster in the past. In fact, when we modify Runnegar's (13) plot of amino acid substitution versus time (=molecular clock) to incorporate changing ^{40}K activity levels over time, the predictions match the fossil record and the results of Valentine's (15) cell-type model much better. We are presently exploring the significance of ^{40}K activity levels though time on evolution and molecular clock theory.

Cells have mechanisms to repair damage caused by exposure to ionizing radiation. These mechanisms appear to have evolved to contend with radiation levels that were nearly an order of magnitude higher than today. Has this ability been retained by life through geologic time? Even if in the geologic past there was no threshold for "safe" exposure to radiation, falling radiation exposure levels over geologic time suggest that there should be a threshold at the present, as suggested by the recent work of Kondo (16). Is it not possible, if not probable, that the threshold is equal to the background radiation levels that existed at the time when this repair mechanism evolved?

WORK IN PROGRESS

We are currently working to resolve several issues. Among these are the composition and opacity of the early atmosphere to UVC radiation, the effects of increased radiation levels and dose in the geologic past on current ideas in evolution and the molecular clock, the chemical composition of Archaean seawater, and the concentration of U, Th, and K in the earth's crust during its formation.

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