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Ionizing radiation – an evolutionary threat?

Georg Steinhauser

ABSTRACT In the aftermath of the Fukushima nuclear accident, it has often been argued by the concerned public that radioactivity and ionizing radiation have to be considered intrinsically harmful because humans have no sensory organ for this type of radiation. It is not only true that humans lack a sense for ionizing radiation, but *no* organism on Earth is known to possess such a sense. In this hypothesis I argue that, from an evolutionary point of view, in fact the opposite of the above argument may well be the case: Is not the lack of a sense for radiation rather indicating that radiation damages have never exhibited a serious evolutionary threat? If ambient ionizing radiation levels, which were much higher in prehistoric times than today, were threatening the health and well-being of populations, why has not any organism bothered to carry the costs of the development of a sensory organ for radiation? Instead, nature developed radiation repair mechanisms to take care of the radiation-induced damage on a cellular and molecular level. A sensory organ for radiation would have taken the response of organisms to another level: it would have allowed those organisms to avoid areas or habitats with high dose rates, provided that radiation exhibited a sufficient evolutionary threat. I hypothesize that the hazards caused by ionizing radiation just have not been regarded as sufficiently evolutionarily relevant to go one step beyond the development of radiation repair mechanisms and cause the evolution of a sense for radiation. The discussion also covers several shortcomings of this hypothesis.

INTRODUCTION The Fukushima nuclear accident has illustrated once again that few health threats elicit a visceral reaction among people as powerful as radiation. Most nuclear scientists and health physicists will agree that, in contrast to the public perception, true radiation risks are seldom within the same order of magnitude as the threats that are communicated by the media and manifested in the public perception[1,2]. It is also widely observed that fact-based arguments rarely help public individuals to overcome their fear[3]. Different strategies have been developed and deployed by health physicists in the public discussion, some of which are more effective or prudent than others. After nuclear accidents, radiation experts, when asked by the media, frequently compare the doses (and associated risks) caused by anthropogenic sources with radiation exposure of natural sources of radiation, e.g. the doses caused by cosmic radiation during flights, or the doses caused by medical X-ray imaging, which most people in industrialized countries have experienced before. Interestingly, the sole experience of a medical imaging procedure implies to the average person that it is harmless, although theoretically it could also deliver harmful doses. As long as the dose does not create deterministic radiation damage, a dose increasing the risk for stochastic, time-delayed radiation damage will always be "experienced" or "felt" as harmless, because of the lack of immediately observable effects. This statement is based on the linear-no-threshold (LNT) theory of stochastic radiation damage. The LNT says, in essence, that the excess-risk of radiation-induced health effects can be extrapolated from high radiation levels to lower levels that are in the range of the ambient, natural radiation level[4]. In this conservative approach, no threshold is accepted below which radiation is regarded as harmless or even stimulating in a positive way. It is very difficult, however, to distinguish between radiation-induced effects and other environmental factors, so that the effects of low doses usually cannot be resolved statistically in randomized epidemiological studies. This explains why our understanding of the effects of low doses of ionizing radiation is still far from complete.

Sometimes radiation experts explain and picture the radiation-induced cancer risk by comparing it with other risk factors,

Illustration by Eloïse Kremer

Department of Environmental and Radiological Health Sciences, Colorado State University, USA

Leibniz Universität Hannover, Institut für Radioökologie und Strahlenschutz, Hannover, Germany

Correspondence: **georg.steinhauser@colostate.edu, georg.steinhauser@ati.ac.at**

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such as smoking, alcohol consumption or other risks from the general human life-experience (such as car driving). I feel that the latter strategy often fails because people do have a personal experience with risks such as car driving, smoking and related everyday life risks, but they usually have no personal experience with radiation. People feel that they are on top of their everyday life risk factors ("I can drive safely" or "I do not smoke much"), but also that they are exposed to radiation without the slightest capability of influencing this exposure and risk because of the lack of a sensory organ.

DEVELOPMENT OF SENSES I have observed that the layperson's fear of radiation often roots in the lack of a sense for ionizing radiation. "Nuclear" is therefore often categorized as an "alien technology", because we cannot see, smell, taste, feel or hear ionizing radiation. In this paper, a fundamental, provocative discussion that is based on this argument shall be started.

What is the purpose of a sense or a sensory organ? "The highest purpose [in nature] is always the same: the preservation of the species."[5] Hence this must also be the ultimate motivation for the development of senses. In the evolutionary process, humans have developed senses for a range of environmental factors. In the most general approach, senses have developed by evolutionary mechanisms to:

a) achieve or enhance the good or

b) avert the detrimental[6].

Senses, therefore, help us find food (or prey) and check its quality, interact socially and find mates. At the same time they help us avert possible hazards and risks such as enemies, predators, parasites, extreme temperature, rotten or hazardous food, chemical toxins etc. They are "peepholes on the world"[7] that provide us with fundamental orientation in our environment. Environmental factors and stimuli will create selection pressure and provide evolutionary advantage to those individuals that, either by random "genetic coincidence" (mutation; the Darwinian approach) or, according to Riedl's view[8,9], after genetic pre-selection, perform better than others. For example, in the words of Smith[7], "The frog with eyes that respond to a small moving object will catch more flies, faster, and can spend more time courting and mating with females than the frog with less sensitive vision. A rat that associates a certain odor or taste with a plant that evoked a past illness will have an advantage over a rat that makes no distinction and wastes time eating poison." In the most generalized approach, those individuals that have developed a better sense than their competitors will perform better in "enhancing the good" or "averting the detrimental".

It goes without saying that humans are not able to sense the entire set of environmental factors, but only selected factors or a selected range within the physical spectrum. Of course, the human range is not the evolutionary benchmark. There are numerous organisms that have developed senses for a wider range of the physical spectrum or more specialized senses for environmental factors that are beyond the human range. To give some examples, the human eye is sensitive for electromagnetic radiation (light) with wavelengths in the range between 400 (violet) and 700 nm (red). There are several prominent examples for organisms that exceed the human range. Some snakes have developed a sense for infrared light that acts as a prey detector[10,11], but may also be used in thermoregulation[12]. It has also been shown that the toadfish, *Opsanus tau*, as well as the little ash beetle, *Acanthocnemus nigricans*, are sensitive to infrared radiation[13,14], proving the great variety of mechanisms evolution deployed to make IR radiation detectable for various animals. Some insects have developed visibility in the ultraviolet range which helps them find blossoms as food sources. Even the rather primitive ciliate *Blepharisma japonicum* was shown to perceive and transduce UV-B radiation as an environmental sensory stimulus, which it escapes from gathering in shadowed areas[15]. Some bats have extended their acoustic wave hearing range into the ultrasonic range allowing them to navigate through the darkness[16]. Sharks can sense electric fields with their ampullae of Lorenzini (thus helping them finding prey)[17], and some birds navigate by sensing the Earth's magnetic field using their magnetoreceptors[18]. The same discrepancy between the human and the non-human range of senses can be found with chemical factors: Although, at high concentrations, CO_2 is a suffocating gas, it is odorless for the human nose; however, some mosquitos have developed a CO_2-sensitive chemoreceptor (helping them find mammals as blood sources via their CO_2 exhalations)[19]. Humans have not developed any of these abilities, because, in the simplest explanation, the lack of these senses has not (yet) created sufficient evolutionary pressure, or the development of these senses has not (yet) created a significant advantage compared with the (evolutionary) costs of their development and implementation.

A SENSE FOR RADIATION? Some human senses are well developed. The human nose, for example, is extremely sensitive for sulfur compounds such as H_2S (stench of rotten eggs). Our tongue is very sensitive for poisons such as alkaloids that have a very bitter taste. Both senses make it possible for humans to ensure the quality and innocuousness of food. Obviously it has been a significant evolutionary advantage to develop these senses although they are probably not equally relevant for all humans, depending on the environment and diet.

In any case, the scientific community is presently not aware of any organism that has developed a sense for ionizing radiation (in order to avert it). Radiotropic fungi seem to seek high radiation environments to "metabolize" the energy of the physical decay[20]. To the author's knowledge, however, it is unclear whether or not they have a "sense" for radiation. In a provocative way, one may ask how evolutionarily relevant ionizing radiation has been regarded by nature, if we do not know any organism that has bothered to develop a sense for this potential threat.

AMBIENT RADIATION BACKGROUND VS. ANTHROPOGENICALLY ENHANCED RADIATION LEVELS Of course the key hypothesis of this study – no sense, no (serious) threat – is only valid for natural, ambient radiation levels and not increased levels by anthropogenic action or even nuclear accidents. We must keep in mind, however, that natural dose rate levels differ significantly (by at least two orders of magnitude) throughout various locations on the globe[21]. There are high-background regions on Earth, for example in Iran[21] or Brazil[22,23], where the natural dose rate is comparable to or higher than what has been observed inside the Fukushima exclusion zone[24,25]. Although no major health problems are observed in those areas with high natural radiation, it is believed that such extreme radiation levels may cause minor physiological changes amongst the local, affected population[26]. Lastly, we must also keep in mind that life on Earth developed long ago when the radiation background due to the presence of shorter-lived primordial radionuclides was significantly higher than today. Karam and Leslie[27] estimated that the ambient dose rates dropped by a factor of 10 since life first evolved. Also, prehistoric fluctuations in solar activity and the intensity of the geomagnetic field, e.g. such as during polarity transitions[28], are likely to have significantly increased the levels of cosmic radiation on Earth (at least locally) – however, this has not created sufficient evolutionary pressure to cause the development of a sensory organ for radiation within any known population.

What could a radiation biodetector theoretically have looked like? One may argue that it would have been difficult for a biological system to bioengineer a radiation detector following the principles of a gas ionization detector or the like. However, it would surely be plausible to argue that nature would have been capable of developing a sense for the degree of ionization in air, thus "smelling" ions as the result of the interaction of high ambient radiation with air. However, this sense would not have been very specific, because there are also other sources of ions in air (e.g. after lightning strikes). Perhaps a biological detector could have followed the principle of the gravity sense of higher animals: biominerals in contact with sensitive cells. In this case, the biomineral had to have scintillating properties and the surrounding cells had to be light sensitive.

Another interesting concept of a new type of detector was presented recently by Griffith and Bayer[29]. The newly proposed detector type is based on the color changes induced in biomolecules by ionizing radiation, in particular the interaction of ionizing radiation with phosphodiester bonds. This "bio-inspired" detector thus mimics an important radiation-induced DNA damage that is also observed in living organisms. Similar concepts of bio-inspired detectors have been used for the development of biosensors for UV light[30]. Evolution could have taken advantage of similar principles. Although this is just speculation, evolution would surely have been innovative enough to develop a sense for ionizing radiation, provided there had been sufficient evolutionary pressure to accept the costs of this innovation.

DISCUSSION I am well aware that the above hypothesis faces some partly serious limitations. Not every threat causes the development of a sense. Very often, the development of repair mechanisms is a sufficient response to an environmental threat factor. It seems that a sensory organ is only developed in cases when the organism is given the choice whether or not it shall be exposed to a threat. For example, humans got a thermosensor, because we are usually given the opportunity to seek cool shadows instead of standing in the hot sun. This is one of the limitations of the above hypothesis: perhaps animals do not have a sense for radiation because they cannot adaptively respond to the presence of elevated levels of radiation. Radiation fields are generally not very localized, which means that, in contrast to stepping into the shade, it will be more difficult to escape high radiation fields. One would have to leave the wider location to experience an environment with lower dose rates. This means that, given the other constraints on animals' choices, there may be nothing they can do with the information of elevated radiation, even if they had it. Perhaps this is the reason why organisms developed sensing mechanisms for the damage that was induced by ionizing radiation on a cellular level, but not a sensor-controller-effector type sensory organ[31,32]. Further, it has been discussed previously[6] that sensory detectors are primarily designed to respond to a rapid change of an environmental factor (e.g., sudden heat, the taste of a bitter berry or the appearance of a predator). Since the changes in the ambient dose rate are not nearly as sudden as those of the other environmental factors, the fundamental concept of all other sensory organs (detection of a rather rapid change) could not have been employed for a hypothetical radiation detector, given the lack of fluctuation in the local radiation fields.

In any case, a sensory organ could have been potentially beneficial for highly mobile animals, such as flying insects or birds, allowing them to escape from a high-radiation environment, if the radiation was regarded as sufficiently harmful. However, it is clear that an "automatic" response to the threat imposed by ionizing radiation on a cellular level, (i.e. repair), excludes the possibility for any imprudent or erroneous response that could result from the signals emitted from a hypothetical radiation sensory organ.

Similarly, a sense for chemical toxins only makes sense if the organism is given the opportunity to avoid the toxin. We may usually have the choice whether or not we want to eat bitter berries, but we do not have the opportunity to avoid toxins that are contained in every possible food item. A rather simplistic example would be, for example, the serious threat caused by water on a molecular level. Hydrolytic reactions may hinder the integrity of genetic polymers, but no organism detects the presence of water – instead, what emerged was a rather large array of repair mechanisms of the DNA. Similar mechanisms for the detection of damage and its repair are known for radiation damage in the cell[32]. It seems these repair mechanisms were sufficient for organisms to avoid serious evolutionary threats.

Apparently, the threat caused by ambient radiation levels did not cause the second level of response by developing a sensory organ. Some organisms, above all *Deinococcus radiodurans*, impressively illustrate the efficiency of existing radiation repair mechanisms. This extremophile tolerates very high levels of radiation. This ability is due to biomolecular mechanisms that included multiple copies of its DNA that first evolved as a response to extreme desiccation conditions[33].

Lastly, we come back to the radiation background in prehistoric times and its impact on the necessity for a radiation detector. Life on Earth evolved primarily under water, 3.5 billion years ago. Vertebrate life, however, became terrestrial only 370 million years ago[34], at a time when ambient radiation levels were already much lower than in the early stages of life on Earth. Perhaps the question of the evolutionary need of a sensory organ (at least in vertebrates) is not justifiable because vertebrates became terrestrial "too late" in the history of life on Earth to experience the early high dose rates in air. Under water, in contrast, even highly penetrating γ-radiation emitted from the sediments or bedrock will be shielded very effectively by the water itself, thus reducing the external exposure of aquatic organisms to a minimum. Any dissolved radionuclides probably diluted quickly in the Earth's gigantic water inventory to harmless concentrations and thus apparently did not cause significant harm to our ancestors through incorporation.

CONCLUSIONS I hypothesize that the lack of a sensory organ for radiation in nature indicates that ambient radiation levels did not impose a significant fitness tax as they were 10 million times lower than the lethal dose of radiation for humans when delivered within one hour[35]. It can be speculated that the benefits of a hypothetical radiation biodetector did not outweigh the costs for its development. This is similar to what has been discussed with respect to protection against cancer[36,37]. The costs for efficient countermeasures against cancer were only carried by large animals; however no organism had to carry the costs of a radiation detector. According to Jaworowski, the ambient radiation levels were not high enough to create sufficient evolutionary pressure for the development of a sensory organ[35].

A sensory organ is developed when it provides crucial information leading to an evolutionary advantage of the respective creature. It seems that ionizing radiation was a somewhat "unnecessary information", and it appears that a hypothetical radiation sense would have been like an answer to a question nature had never asked. Instead, evolution provided us with an array of repair mechanisms, which included detection systems for radiation-induced damage on a cellular level. Up to now, it seems that the implementation of repair mechanisms was a sufficient evolutionary response to environmental levels of ionizing radiation.**H**

CONFLICTS OF INTEREST Author declares no conflicts of interest.

ABOUT THE AUTHORS Georg Steinhauser received his PhD in radiochemistry from Vienna University of Technology (Austria) in 2005. In 2007, he worked at Ludwig-Maximilian-University in Munich (Germany) as an Erwin-Schrödinger-Fellow of the Prof. Thomas M. Klapötke group. Back at the Atominstitut in Vienna, Steinhauser was in charge of the radiochemistry laboratories from 2011 until 2013, when he was hired by Colorado State University as an assistant professor. In 2015, Steinhauser was hired as a professor for physical radioecology by Leibniz Universität Hannover (Germany). His fields of activity include environmental analytical methods and the development of nuclear forensic methods with main focus on the Fukushima nuclear accident.

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