Stem Cell & Translational Investigation 2016; 3: e1359. doi: 10.14800/scti.1359; © 2016 by Asaf Durakovic
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REVIEW

The specter of plutonium in modern warfare

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Received: May 23, 2016
Published online: June 29, 2016

The current global reality of the re-emergence of the Cold War, migration of large segments of the global population, depletion of natural resources, and the ever-increasing need for alternate energy presents existential challenges to geopolitical unresolved crisis, and ultimately, stability of the biosphere. While the strategic nuclear confrontation is an unlikely scenario because of its irreversible consequences, tactical warfare is a realistic probability of the outcomes of regional and geopolitical differences around the globe. The fragile and limited scope of the stratosphere, including the airspace and waters, provides ever-decreasing probabilities of expansion, limited options for sustainable life, and increasing risk to the survival of the environment. The industrial pollution is enhanced by the nuclear age radioactive environment, which is irreversible in light of man-made insults to the biosphere by the nuclear-era civilian and military release of the man-made imbalance. Non-proliferation nuclear treaties, to which not all countries are signatories, do not provide a prospect of security for mankind in the current polarized geopolitical realities, enhanced by clandestine use of nuclear-era destructive powers and by settling regional differences in the confrontational rather than compromising manor. Current realities of the instabilities of the Middle and Far East, large segments of Euro-Asia, shifting of the military priorities, and unceasing production of the nuclear arsenals appear a challenge not only to the well-being, but to sustainable homeostasis. Radiation dispersal devices, nuclear terrorism, renewable energy challenges, chemical and radioactive pollution, melting of the polar caps, and global warming present existential challenges to this fragile segment of the galaxy. The advent of transuranic elements, exemplified by plutonium, adds a recent relatively new dimension to the challenges facing the biosphere. This article attempts to objectively assess the role of radioactive pollution by actinides in the current global reality.

Keywords: transuranic elements; plutonium; radioactive pollution; preventive medicine; radiation dispersal devices; nuclear terrorism

To cite this article: Asaf Durakovic. The specter of plutonium in modern warfare. Stem Cell Transl Investig 2016; 3: e1359. doi: 10.14800/scti.1359.

Introduction

The current reality of the nonconventional global confrontations and the lessons learned from the Gulf War, including Afghanistan, Iraq, the Balkans, and Gaza, present an opening challenge extending far beyond tactical battlefields, to the general scope of environmental medicine, and to the strategic impact of the modern warfare.[1] The advent of radioactive dispersal devices (RDDs), while not totally new to the concepts of large scale warfare, has become particularly important since the deployment of depleted uranium-containing weapons.

The concept of the use of radioactive-containing ammunition was contemplated by the Axis Alliance in World War II, but it was derailed to the other scenarios in the shifting priorities of the European warzone and subsequent nuclear accidents. The impact of radioactive components of nuclear weapons thus shifted to the cataclysmic reality of the blast, heat, and external radiation, leaving the legacy of the resulting contamination of large parts of the continent to the concerns of environmental medicine, internal radionuclide contamination, and radiation toxicology [2]. While nuclear weapon fission results in the release of over 400 radioactive isotopes, among which over 40 are organotropic and particle radiating radionuclides, their transuranium component presents an insurmountable challenge to the biosphere and public health [3]. The primary concern of uranium is that it is one of the primordial elements of the universe with the half-life of some of its isotopes matching the age of the universe [4]. Whether or not the low-level radioactivity of some of uranium isotopes are of pragmatic impact to the biosphere and mankind, the fact remains that they do contain alpha radiation and other corpuscular emissions, the impact of some not even yet being comprehended [5].

Transuranic elements

Uranium, the heaviest metal, is a primordial element of the quantum universe with currently identified 27 radioisotopes [6]. Its 4 isotopes (234, 235, and 238) are part of the natural world, with U-236 being artificially produced. All contain high ionizing potential by their corpuscular properties amplified by long half-lives ranging from micro-seconds to billions of years, and some will outlast the present universe, exemplified by uranium-234, which is 17 times more radioactive than U-235. The modern radioactive battlefield, however, is a new advent of the impact on the biosphere partially because of depleted uranium (DU), a byproduct of the enrichment process of natural uranium to the weapon grade and which presents as a hazard of internal contamination by its osteotropic properties and the ultimate incorporation in the bone crystals and pluripotent stem cells, as well as by the impact of its nephrotoxic properties, particularly in the proximal convoluted tubules [7]. The low level radioactivity of U-238 has to be considered in light of its alpha emissions and its long half-life, as well as its decay radionuclides, including thorium-234 and protactinium-234, alpha emitters with half-lives of billions of years [8].

The production of plutonium started in the beginning of World War II, with still current controversy of its origin in French cyclotron, then in the hands of Nazi Germany, or at the university of Berkley, produced by the work of Glen Seaborg and being shrouded in the secrecy until the Manhattan Project on the potential component of the nuclear weapon after the separation of plutonium from uranium. The name uranium, however, goes back more than two centuries earlier when Martin Klaproth, in studying silver, discovered what he called a “strange kind of half metal” as a component of a black mineral, being the heaviest of all naturally-occurring elements [9]. He named it after the planet Uranus. Subsequent discoveries of nuclear fission were marked by the milestones in nuclear physics with the discoveries of the secrets of the nucleus by Hahn, Meitner, and Heisenberg. The political collisions between the objective science and Nazi Germany did not, however, delay the current scientific discoveries, followed by the advent of transuranic elements and element 93 in 1938. The focus of nuclear physics switched to the United States at that time with prominent work by Glen Seaborg and, among others, Berkley University, Princeton University, and the constellation of scientific communities and universities of America. A neutron capture of uranium-235 transmuted it into uranium-236, with a Noble Prize in physics awarded to Enrico Fermi in 1938. Splitting of the nucleus by the slow neutrons reacting with uranium-235 resulted in uranium-236 and a neutron and lead to elements 93 and 94 [10]. Beta decays into element 94 – plutonium. The resulting discovery of uranium tetrafluoride led to the discovery of uranium hexafluoride, and Seaborg’s discovery demonstrated by the slow neutrons that the new element had more fissionable properties than uranium. It was the discovery of pluttonium-239, named after the mythological guardian of the gates of hell, Pluto. The crack opened in the “gates of hell” over Nagasaki on August 6, 1945.

The metabolic pathways of transuranic elements have been extensively studied and summarized in the publication of the University of Rochester 1949.[11] The ultimate target organ of actinides is the skeletal tissue with predilection sites along endosteal surfaces and in the exchangeable ($CaHPO_4$) or nonexchangeable crystals or hydroxyapatite ($3Ca_3(PO_4)_2$ $Ca(OH)_2$), modeled by fluorapatite as the theoretical prototype [12]. Such crystal probably does not exist in the natural bone because of the dynamic metabolic exchange by the isoionic or heteroionic interactions between the extra-cellular fluid and the bone. For that reason, other elements can become a part of the bone crystals by the chemical exchange or physical chemical apposition. Among them, the products of nuclear fission, upon gaining access to the internal environment of the body, can become a part of the bone including nuclear fission products released into the biosphere by the nuclear weapons, industrial accidents, or environmental pollution. As the bone minerals of either trabecular or compact bone, whether in cancellous bone or in the compact bone diaphysis, they are ultimately incorporated in the vicinity of the bone cells or pluripotent stem cells – the most radiosensitive cell population of the living organism.

The consequence is hematogenic or oncogenic transformation. Transuranic elements in the internal environment present a lasting hazard by both corpuscular radiation and long half-lives, in addition to genomic changes exerted to the genetic code of macromolecules with trans-generational consequences.

The final deposition of transuranic elements in the bone as the target organ is determined by the pathway of contamination. In the event of atmospheric nuclear testing, an average of 0.2 ng/m3 is the natural burden in air samples of Japan, 0.6 ng/m3 in England, 0.4 ng/m3 in New York City. Retention in the skeleton averages 4.4 µg/kg in Japan and 3.0 µg/kg in England in the average population. From the inhaled uranium, metabolic pathways transport it to the rest of the body, where it exerts nephrotoxic effects by its chemical effect on the tubules. The carcinogenic and mutagenic properties are well-studied and documented. The uranium dust particles behave differently in the upper and lower respiratory pathways. Eighty-five percent of UO3 is excreted by the kidney from the systemic circulation with 65% retained in the bone and 40% excreted in the urine.

Depleted uranium (DU) metabolic pathways have been studied in British, Canadian, and United States veterans up to 9 years after exposure to radioactive dust in the Gulf War I [13]. Twenty-seven veterans exposed to DU showed evidence of inhalational exposure to DU and were analyzed for the presence of 4 uranium isotopes (235, 236, and 238) with the ratios of 143.2 in the lungs, 140.2 in the liver, and 147.8 in the bone, demonstrating presence in the body tissues after inhalational exposure. These results have been consistently reproducible and also confirmed by the studies of the bone samples of the deceased veterans of the Gulf War. DU was present in 14/27 samples and the results confirm definitive presence of uranium-234 and uranium 236 after inhalational exposure.

The numerous studies have consistently demonstrated the connection between uranium and plutonium with malignant alterations in the skeletal tissues. It has been connected with radioactive fallout by recent Russian studies of uranium and plutonium in the bones of the population living in the area of Kazakhstan's nuclear test site in Semipalatinsk [14]. The studies were conducted by alpha spectrometry and related to the global radioactive fallout in the 1980s. They were over ten times higher than exposures of the populations of Japan and New York City and were the consequence of the inhalational exposure to uranium-containing dust. These studies were confirmed by the high resolution ICP-MS methodology with the evidence of the isotopes of plutonium in the soft tissues and bones of the residents of Kazakhstan autopsy samples. Plutonium-239 and 240 were detected by the high resolution plasma mass spectrometry. The bone and kidney samples were higher in the concentration of both isotopes than the average global fallout [15].

These studies are consistent with the reports of plutonium isotopes in French Polynesia with the evidence of plutonium-239 and plutonium-240 in the surface and deep waters of the Atolls in Polynesia. These were conducted by plasma mass spectrometry, and the samples were collected in the ocean waters as far as 1,000 miles from the French nuclear test site [16]. It was further confirmed by the reports of the incidence of cancer and mortality in the population living in the vicinity of uranium sites of New Mexico [17] and the geographically distant population of the African country of Namibia, where uranium mines are also located [18].

Carcinogenic properties of uranium were suggested of being dependent on chemical and isotopic composition of uranium in French nuclear industry workers [19] and Russian population of the Mayak region [20]. These studies are well in agreement with the earlier reports of the effects of global radioactive fallout of three decades ago of plutonium isotopes in the environment after nuclear accidents in Thule (Greenland) and Palumaris (Spain) [21]. The fallout was directly linked to the nuclear accidents of 1966 and 1968 respectively. The plutonium in these samples was determined by the high resolution alpha spectrometry and x-ray spectrometry and are consistent with weapon-grade plutonium. The human data have been consistent with numerous reports on animal studies, particularly the reports on the liver and skeletal retention of plutonium-239 in dogs and rats [22]. The liver and skeleton data on these animal species, as well as excretion pathways, demonstrated similar metabolic behavior [23].

Actinide data have been evaluated in light of the other osteotropic elements exemplified by the mineral seeking alkaline earths. The alkaline-earths-nuclear-fission-produced-radio-isotopes have been compared with actinides in human bones in the surgical and autopsy samples in the studies of southern Poland and provided a reference point for the estimate of contamination studies of the general public [24]. Americium-231, plutonium-239, plutonium-238, plutonium-240, and strontium-90 distribution was compared in the bones of the population of Poland and related to the fallout of the Chernobyl accident [25]. The studies were conducted in human bones by mass spectrometry and did not confirm statistical differences between the population of southern and northern Poland. In another study, the residents of Los Alamos had higher concentrations of plutonium in the lungs than non-residents by the studies of the human autopsy data [26].

Nuclear-fission-produced-radioisotopes, whether a result of nuclear weapons or nuclear industry accidents, presents a standing challenge to the environment and industrial and occupational medicine. It is an almost unanimous conclusion that their representative examples are strontium-90 and plutonium-239, the latter being considered as the most toxic substance known to man. A retrospective study of the Swiss population has demonstrated that plutonium retention has a half-time of over 40 years while strontium is approximately 14 years [27]. While the osteotropic properties of plutonium are well known, its micro distribution in skeletal tissue has been studied by the validation of dosimetry models. The human skeletal tissue was studied for the assessment of plutonium incorporation in the bone by quantitative analysis neutron-induced autoradiography and the micro bio distribution of plutonium was analyzed for both cortical and trabecular bone [28]. The results were consistent with the established facts of significant difference in the metabolic behavior between bone surfaces and the compact endosteum. These results have been further confirmed by the studies of surface-seeking radionuclides in the humans and dogs [29], as well as the herbivorous rodents in Poland [30].

The carcinogenic models of incorporated radium, strontium and plutonium were compared for the bone-seeking radionuclides and reported their dependence on the dose rate [31]. The ultimate retention site of the osteotropic radionuclides, whether endosteum, matrix, or crystal-seeking, is the environment of the vicinity of the stem cells with the consequence of malignant alterations, including leukemia and osteogenic sarcoma with the well-known consequences [32].

The potential effects of transuranic elements, and in particular plutonium-239, as a possible consequence of nuclear proliferation or clandestine use in terrorist scenarios, presents a challenge to the potential genomic stability of the biosphere and mankind. The issue of particular concern is the scenario of the terrorist use of organotropic radioisotopes in mega cities of the industrial world. A radiological dispersal device, or "dirty bomb," does not contain the component of the destructive potential of the nuclear weapon. It would however present close to insurmountable logistical problems and disruptions [33].

The history of plutonium begins with the discovery of uranium by silver miners in the mountainous region of Saxony, Germany, during the 16-18th centuries [34]. Martin Klaproth, a chemist, was the first to study the shiny black mineral in 1789. He decided to name it after the planet Uranus, earlier discovered by his countryman William Herschel. Subsequent terminology, largely compiled by Dimitri Mandeleev, was partly based upon Sanskrit numerology under the influence of his friend Otto Bohtlingk, who was a scholar of Sanskrit at the university at St. Petersburg, which later included the term plutonium, named after Pluto. Subsequently-discovered properties of plutonium justify its name. With this mysterious element properly shrouded in the Dante's secrecy of Pluto's undecipherable exclamation at the seventh circle of Hell: "Pape Satan aleppe – so echoed the shrill voice of Pluto [35]."

Transuranic elements include all elements beyond the atomic number 92, which is uranium. All of them are radioactive and can be synthesized by bombarding a heavy element with a light particle or element. Most of them have long-half lives, including several with half-lives of over 5 billion years, meaning that some transuranic elements will outlast the quantum universe.

Radiological dispersal devices

The use of uranium isotopes and some tranuranium alpha-emitting radionuclides presents a formidable challenge to the biosphere because of their long-half lives, particulate disintegration, ionizing capacity and organotropism. Their use in RDDs opens an entirely new chapter in the area of the radiation toxicology with their adverse impact of the structure and function of the living organisms, including human population, not only on the current population of the planet, but also on the genomic stability of the future generations. RDDs, such as a radioactive "dirty bomb," present the ultimate challenge to mankind largely due to the logistical impossibility of dealing with the consequences.

RDDs are likely to be used in the tactical nuclear war scenarios or in terrorist attacks. Recent literature abounds with the reports on the possible consequences of radiological and nuclear terrorism, predicting its almost inevitable advent in the future global areas of confrontation [36]. Scenarios involve potential military or industrial targets, particularly in the densely-populated areas. Preparedness algorithms have been extensively studied in both civilian and military scenarios [37]. Recent reports almost uniformly predict the inevitability of nuclear and radiological terrorism, necessitating a need for radiology and nuclear disaster training, which is currently sub-optimally addressed in the curricula of continuing education [38]. While disaster preparedness for tactical war and terrorist scenarios are being extensively studied, they are still in the area of insufficient preparedness all around the globe [39].

In 2012, Defence Research and Development Canada led a series of experiments, called the Full-Scale Radiological Dispersal Device (FSRDD) Field Trial, in which short-lived radioactive material was explosively dispersed [40]. Various

organizations and researchers have recently used these trials [41] to evaluate the performance of dispersion models [42], to measure and characterize the ground deposition [43], and monitor the spread of radioactive materials in the atmosphere [44]. Currently, the other models of radiological risk assessment are being studied with the most recent RDD models [45], some emphasizing the management of RDD-exposed patients in the different contamination scenarios and evaluation by Monte Carlo Code for the different ages and taking into account various management scenarios. The conversion coefficients established are being used for the estimates of the effective doses and implications for the health care providers in RDD scenarios [46].

The radiological and nuclear accidents currently accelerate to the level of high risk events with the significant impact on the general public. The morbidity and mortality in the population is related to the hospital-based management including a need of enhanced preparedness of interventional radiology and nuclear medicine. It also necessitates the preparedness of security and safety measures with special emphasis on RDD components. The psychological impact and the disruption of the affected segments of society are mitigating circumstances due to general panic and disruption of life. General communities are largely unprepared for such catastrophic circumstances with the need of correcting current weaknesses in preparedness and improvement in disaster medicine [47]. Both short term and long term effects of radiological and nuclear accidents need to be better addressed to meet the future challenges [48]. These potential events have also been studied in the large-scale scenarios [49]. In the events of the deployment of RDD the response of the emergency and pediatric medicine for the improvement of readiness is also urgently warranted [50].

In the pending prospects of the nuclear and radiological regional and global events, complacency will not be rewarded in either short-term events or RDD deployment [51]. The current political geography, economic migrations of large segments of global population and the ever-increasing need for agriculture and energy do not essentially contribute to the well-being of mankind. Confrontation rather than peaceful coexistence is a more pragmatic probability of the more densely populated planet submerged in the environmental disadvantages of polarization, and industrial and radioactive pollution.

Conflicting interests

The authors have declared that no conflict of interests exist.

Acknowledgements

The author thanks Dr Julianne Hazen for the valuable review of this manuscript.

Author contributions

A.D. conceived the idea, conducted the research, analysed the outcomes, and authored the manuscript.

Abbreviations

RDD: radiological dispersal devices; DU: depleted uranium; ICP-MS: inductively coupled plasma mass spectrometry; FSRDD: full-scale radiological dispersal device.

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