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Retrospective dosimetry of populations exposed to reactor accident: Chernobyl example, lesson for Fukushima

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HIGHLIGHTS

► Retrospective dosimetry in Chernobyl was applied for evaluation of individual doses to evacuees.
► Retrospective dosimetry in Chernobyl was applied for validation of ecological dosimetric models, rejection dubious dose rate records.
► Retrospective dosimetry in Chernobyl was applied for risk assessment of leukemia among Chernobyl clean-up workers (liquidators).
► Retrospective dosimetry in Chernobyl was applied for study of cataracts among liquidators.
► Experience of dose reconstruction in Chernobyl could be used for retrospective assessment of exposures in Fukushima.

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ABSTRACT

Follow-up of the Chernobyl accident had included a good deal of retrospective dosimetry and dose reconstruction. Comparison of Chernobyl and Fukushima shows that despite some differences in course and scale of the two accidents, main elements are present in both situations and Chernobyl experience could be quite educative for better understanding and more optimal handling of Fukushima Dai-ichi accident consequences. This paper contains review of dose reconstruction efforts done to date and extensively published in scientific journals and reports. Specifically the following cases are considered: (i) evaluation of individual doses to evacuees; (ii) validation of ecological dosimetric models and ruling out unconfirmed dose rate measurements; dosimetric support of (iii) case–control study of leukemia among Chernobyl clean-up workers (liquidators), and (iv) cohort study of cataracts among liquidators. Due to limited size of this paper the given application cases are rather outlined while more detailed descriptions could be found in relevant publications. Each considered Chernobyl case is commented with respect to possible application to Fukushima Dai-ichi situation. The presented methodological findings and approaches could be used for retrospective assessment of human exposures in Fukushima.

1. Introduction

Unfortunately, the experience of peaceful use of nuclear energy had proven that this technology is inevitably associated with a risk of radiological emergencies, in some cases - of large scale. Three-Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents had different origin, nature and degree of radioactive release, but this history shows that there is non-zero probability of radioactive release, which will lead to significant exposure of workers (both personnel and emergency responders) and members of public residing in adjacent territories. In general, such accidents happen unexpectedly, evolve rapidly with originally unknown outcome and are associated with discharge of radioactive materials outside controlled area and guarded perimeter of a nuclear facility. Upon release from the confinement, radioactive materials in a form of dust particles and aerosols are transported to environment by air, aquatic systems as well as mechanically by contaminated men and vehicles. Doses and dose rates decrease rapidly with distance from the release point and decline with time after a release. However both time course and spatial pattern of dose rate fields, as a rule, are very complex and cannot be described by trivial formulae. A number of physical processes (heating, melting, evaporation), meteorological and geochemical factors (wind strength and direction, precipitation, solubility and

Abbreviations: ADR, Analytical Dose Reconstruction; ChNPP, Chernobyl Nuclear Power Plant; FISH, Fluorescent In Situ Hybridization; ODR, Official Dose Record; RADRUE, Realistic Analytical Dose Reconstruction and Uncertainty Estimation; SRU, State Chernobyl Registry of Ukraine; UACOS, Ukrainian-American Chernobyl Ocular Study.

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biological availability in soil etc) have effect on formation of contamination patterns. Behaviour and movements of involved humans also add variability to doses received by individuals – both workers and members of public. Therefore, assessment of radiological impact on humans and environment, monitoring, reconstruction and forecast of individual and collective doses are of great importance and takes of good deal of efforts in course of remediation after the accident and follow-up of its consequences. This publication is devoted to review and discussion of the main post-Chernobyl efforts aimed at retrospective reconstruction of doses of external exposure, received by several populations involved into the accident – evacuated population, emergency and clean-up workers (liquidators) as well as permanent residents of contaminated territories. Presentation is organized in a form of cases, which were practically addressed in Chernobyl but also might be applied in Fukushima situation. These cases were published in scientific press with different degree of details, some – quite comprehensively. Therefore, this paper will give more details of less publicized projects and will provide only brief narrative of others along with specific references, where complete details can be followed.

1.1. Generic course of a large scale reactor accident and implications for dose assessment

Time evolution of a reactor accident is quite complex, goes through several phases and has significant effect on irradiation of humans and environment.

At the initial phase of an accident radioactive noble gases and some aerosols as well as mechanically discharged dust and larger debris are released into atmosphere following breakup of a confinement.

Early (acute) phase of an accident is associated with continuing release of radioactive materials when both dose rates and doses to humans are dominated by isotopes of iodine and other short-lived radionuclides. Iodine is particularly significant due to exceptional biological availability (passage through food chains) and ability to concentrate in a small-sized organ – thyroid. As a result, doses received by thyroids of persons exposed to release could be substantially high, overwhelming exposure of other organs or a whole body. During this phase such pathways as inhalation and ingestion via leafy vegetables (if accident happens in warm season) could play significant role. Fortunately, all radioactive isotopes of iodine have short half life and after several months after beginning of a reactor accident (and respective termination of chain reaction in a core) doses formed by iodine radionuclides become negligible. The mixture of other dosimetrically significant radionuclides depends on particular scenario of the accident and, to a large extent, is determined by reactor inventory and core temperature at the time of release. For instance, in course of Chernobyl fire the temperature was so high, that refractory radionuclides with boiling point above several thousands degrees (cerium, ruthenium, molybdenum, zirconium etc) were released into atmosphere. Contrary to this, in Fukushima the temperature of the core was much lower, so virtually none of this staff was found in the environment, while more volatile elements (iodine, cesium, tellurium) were found in the release and deposition after both reactor accidents.

The early phase of an accident is followed by intermediate (stabilization) phase, when external exposure is dominated by short-lived gamma and beta emitters, intakes are formed by ingestion via root intake. At this stage the release is already over, further evolution of dose rate fields and contamination patterns are determined by decay of short-lived radionulcides, vertical migration in a soil and, to lesser extent, by horizontal migration with resuspension and wash-out processes. In general, dose rates and total activity of contamination during this phase go down relatively fast.

After 2–3 years after the accident the aftermath comes to late (recovery) phase when dose rates, contamination density and burden of both foodstuffs and humans stabilize at lower level. This phase could last for decades and further reduction of doses is very slow being mainly defined by half-lives of long-lived radionuclides like ^{137}Cs or ^{90}Sr. The doses and dose rates go down by several orders of magnitude, coming to nearly background levels in few decades.

This generic course of a reactor accident has also another dimension related to exposure of populations, engaged into it. Since large scale radiation emergency happens without even a short notice and catches population and authorities by surprise, initial hours and days are usually characterized by sheer lack of information on dose rates, release, nuclide composition, radioactivity transport processes etc. Later an amount of dose-relevant information grows exponentially, but initial phase (when radiation hazard is the highest) misses any data on personal exposures. Moreover, insufficiently investigated time and space patterns of contamination have negative effect on planning and optimization of radiation protection measures (like selection of safe routes, advise on sheltering etc.) – both for workers and public, leading thus to higher exposure. Although particular details and reasons of this situation may differ in different scenarios, general tendency is quite universal and is illustrated at Fig. 1 – with time passing, the dose rates decrease significantly while amount of information starts from virtually zero and then grow to satisfactory level, yet when significant fraction of a dose had been already delivered to exposed populations.

From the point of view of radiation protection and assessment of doses received by workers, emergency respondents and public this means the need for retrospective dose assessment to be applied in order to recover missing dosimetric information and fill the gaps in essential data, specifically related to early phases of a reactor accident. Besides, retrospective dosimetry should be employed for evaluation of dosimetric quantities (like doses to lens or skin), which were not measured at time of exposure (due to inadequacy of measurement tools or other reasons). Another significant application domain for retrospective dosimetry is related to validation of tentative and, as a rule, rough dose estimates, which were done under significant time pressure and are based on incomplete data and simplified models.

1.2. Applicability of dose reconstruction techniques to post-accident retrospective dosimetry

The plausible methodologies, which could be applied for retrospective reconstruction of individual doses after a large scale reactor accident are the following:

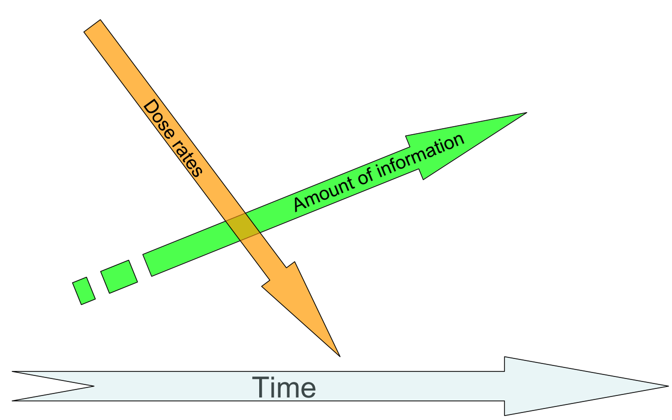

Fig. 1. Relation between dose values and amount of information in course of the large scale accident.