Forensic and medical aspects of radiation accidents investigation

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1. Introduction

Practical experience of radiation emergency response [1] can be used in the investigation of cases involving unauthorized use of ionizing radiation sources. Investigation of radiation accidents with fatal and non-fatal lesions sometimes is very difficult. Results of biomedical and instrumental analyses, carried out after the emergency medical activities, are important and sometimes crucial to establish details of the accident. Based on them, the experts can substantially assist in the investigation: help to formulate possible versions of an incident and determine further investigative leads. The following aspects should be taken into account within such biomedical analyses.

2. Internal Exposure

Based on the experience, summarized in a number of special publications [2-6], the following radionuclides, widely used in industry and medicine (or resulting from the operation of ionizing radiation sources), are generally accepted to be radiologically dangerous: ^{3}H, ^{241}Am, ^{137}Cs, ^{60}Co, ^{131}I, ^{210}Po, $^{238,239}Pu$, ^{252}Cf, ^{192}Ir, ^{235}U, ^{226}Ra, $^{89,90}Sr$, ^{144}Ce. These radionuclides are alpha and beta emitters (except for cobalt, and cesium, which are gamma-emitters). So, they may cause radiation damage primarily in case of intake into the body. There are several routes of intake of radionuclides: inhalation (with inhaled air), ingestion (with food and water), through intact or burned skin or wounds. The main routes of intake, transfer and excretion are shown in Fig. 1.

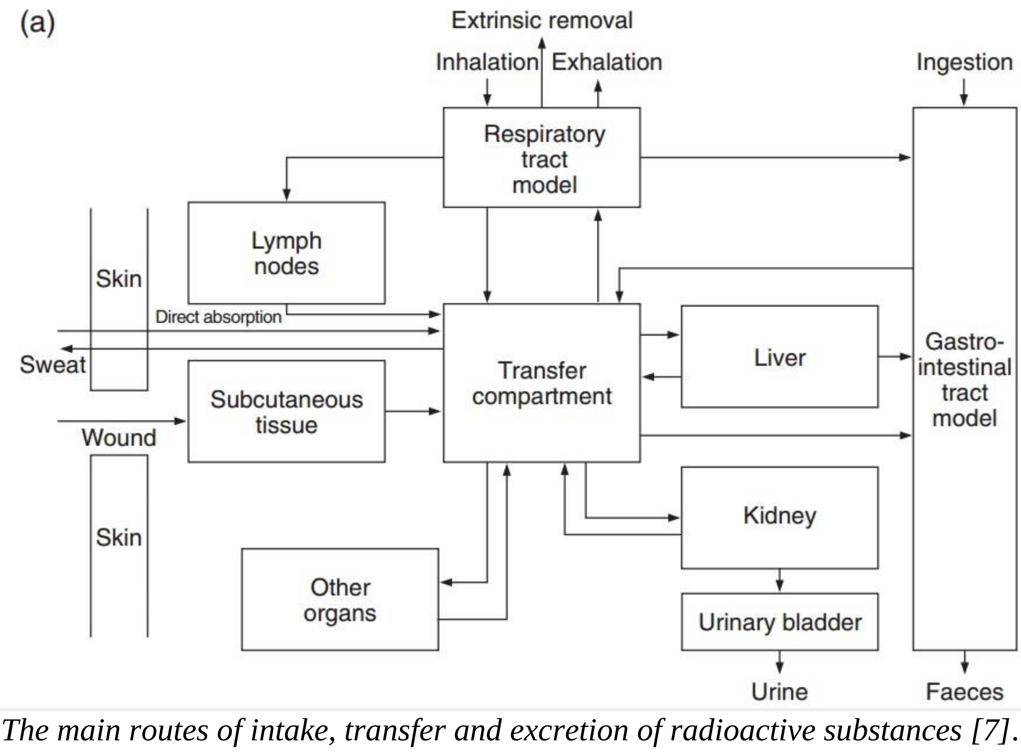

FIG. 1 The main routes of intake, transfer and excretion of radioactive substances [7].

In case of inhalation of radioisotopes the degree and nature of lesions of respiratory organs depend primarily on absorbability of them across the air-blood barrier after deposition on the surface of respiratory tract. It is directly related to the type of an incorporated radioactive chemical compound. There are three types of chemical compounds in terms of rate of transition of the deposited radioactive material into the internal environment of the body: F - fast, M - medium, S - slow [8]. Hardly soluble radioactive substances or their compounds are partly removed from the airways with mucus due to work of the ciliated epithelium. The rest is retained in the lung tissue and has mainly local effect, which can lead to development of deterministic or stochastic effects of varying severity.

In case of contact with intact skin radioactive substances cause local injuries. The rate of their development and severity depend on the absorbed dose and the rate of absorption of the radioactive material.

In cases of intake of radioactive substances through the gastrointestinal tract the following facts must be considered. Substances with low absorption ability (less than 5%) have mainly local effect. Well-absorbed radioisotopes (15-20%) are transferred into the blood and then uniformly distributed throughout the body or selectively concentrated in organs and tissues of main deposition (organotropic) [9-11]. ^{137}Cs, ^{3}H and ^{210}Po are usually uniformly distributed throughout the body. ^{238,239}Pu, ^{241}Am, ^{89,90}Sr, ^{235,234,238}U, ^{224,226}Ra, ^{131}I are organotropic radionuclides. The organotropic radionuclides can be divided into the following groups: (1) osteotropic, (2) mainly deposited in liver and bones. A number of radioisotopes with low absorption ability can cause ulcero-necrotic changes in the gastrointestinal tract in case of ingestion.

In particular, ^{144}Ce oftener affects distal small intestine, ^{241}Am - duodenum and small intestine, ^{239}Pu - colon. Also, keep in mind that there is no system failure of blood and gonads in cases of ingestion intake of radionuclides not combined with external irradiation.

When transferred into the blood through skin, lungs or intestines radioactive substances selectively concentrate in organs of main deposition. So, the signs of internal radiation lesions due to accumulation can be observed in clinical and pathological-anatomical characteristics of radiation sickness caused mainly by internal exposure.

In particular, 90% of the radioactive strontium is deposited in bones, predominantly in metaphyses of long bones and a spongy layer of trabecular bones (e.g. in sternum), causing even in the early days deep distortion and suppression of normal physiological bone formation, which does not occur in case of acute radiation disease due to external exposure.

^{131}I is rapidly accumulated in the thyroid regardless of intake pathway. One can observe extensive hemorrhages in soft tissues of neck and in thyroid, destructive changes up to focal or total necrosis of thyroid parenchyma (bleedings occurring at the beginning of radiation disease are usually mild).

In case of intake of transuranic elements (Pu and Am) up to 90% of the total activity transferred into blood is deposited in liver, and to a lesser extent in kidney. ^{137}Cs is predominantly deposited in heart muscle. So, lesions of mentioned organs can be observed at autopsy.

If intake of radioactive substances is suspected (or there is reliable information), it is important to confirm this information using *in vivo* or *in vitro* analyses in order to determine pattern of distribution of radionuclides through tissues and organs of the body and level of their radioactivity.

In order to assess intake of radioactive material and internal dose it is necessary to have the following:

(1) Metrologically certified procedures of radiochemical analysis, including the analyses selective to the required radionuclides;

(2) Accepted measuring instruments, including whole body counters, radiometers and spectrometers;
(3) Verified computational techniques, including the techniques using the Monte Carlo method;
(4) Specialized software that allows you to assess the intake and doses. In addition, the specialists should have the research protocols approved by the relevant authorities. Sampling and subsequent analysis according should be carried out in accordance with such protocols.

In cases of suspected intake of gamma emitters first of all a survey using whole body counter should be carried out (*in vivo* analyses). If intake of beta-or alpha-emitters is suspected biophysical studies come to the fore (*in vitro* analyses using the appropriate equipment: radiometers for measuring of total alpha and beta activity, alpha- and beta- spectrometers, LS (liquid scintillator) spectrometers, mass spectrometers). The procedure of sampling is very important for biophysical analyses. Sampling of organs must be performed in accordance with the anatomical standard: pieces of organs and tissues (weight not less than 30-50 g) should be taken with clean tools and put in chemically clean vessels without using fixative, the vessels should be tightly closed and sealed. The analysis of biological secretions: nasal swabs, samples of feces and urine, for the content of radioactive substances is of particular importance while patient examination. Biophysical analysis of urine and feces is efficient in terms of assessing the levels of intake and retention. Excretion of radionuclides with urine or feces is irregular. So, the daily amount of excreta for several consecutive days should be collected. Use clean, tightly sealed containers.
Intake and internal dose can be assessed on the basis of the measured levels of excretion and retention using the published models of biokinetics of radionuclides, similar to the one shown in Fig. 1. Moreover, in some cases, certain assumptions about the nature of a radioactive substance and timing of intake can be made.

3. External exposure

In case of external exposure, different conditions of irradiation have different effects on clinical and anatomical characteristics of radiation injury. This is due either to a different degree of severity of pathoanatomical changes or specific localization of the most pronounced effects, or various sequels of the prior disease (e.g., infection).
It is important to consider qualitative and quantitative characteristics of pathological processes in order to help assessing the morphophysiological picture. It is necessary to assess the full range of different conditions, which could cause the main damage.
In emergency situations absorbed dose of ionizing radiation for each case of radiation injury sometimes is not known. At the same time, such information is necessary. Instrumental (eg, EPR spectrometry, phantom modeling) and medical and biological methods can be used to get such estimates In fatal case, if no measurements or estimates of levels of external doses are available, pathologist or forensic expert performing autopsy of a person died from radiation sickness (or if radiation sickness suspected) should try to estimate absorbed dose on the basis of pathoanatomical changes.
To date a number of methods of biological dosimetry, which allow rather accurate assessing of total and local absorbed doses on the basis of early reactions of an irradiated person, have been developed. Objective criteria such as rate of development, type and extent of chromosomal damages in red blood cells, skin reaction (primarily its severity on different areas of skin should be estimated) are used for this purpose.

There are unlimited variants of non-uniform exposure with a primary direct effect of ionizing radiation on a particular part of the body. So, it is important to identify the basic scenarios where the absorbed dose to head, chest, abdomen or limbs is maximal:

- In cases of non-uniform external radiation exposure a pathologist should take into account that an isolated or predominant exposure of head to large dose leads to lesion of its skin, mucous membranes of mouth and nose, eyes and brain;
- Irradiation of chest results in lesion of lungs, heart muscle, spine (with peripheral spinal disorders), bone marrow of sternum and vertebras;
- Irradiation of abdomen and pelvis results in lesions of small intestine up to development of ulcero-necrotic changes and peritonitis. Sometimes it may result in lesion of colon and other internal organs, e.g. kidneys;
- Irradiation of limbs results in lesions of skin and skeletal muscles.

Macroscopic and especially microscopic examination of hemopoietic organs of a deceased is of particular importance in order to establish presence / absence of significant differences in condition of bone marrow, taken from different parts of the body, as well as the discrepancy between severity of suppression of hematopoiesis and characteristics of peripheral blood.
An example of non-uniform gamma exposure resulted in a massive heavy lesion of intestine (120-160 Gy), spine (50 Gy) and lumbar spine is the case of radiation injure described by N.A.Kraevskiy, 1962 [12]. Aplastic anemia in vertebral bone marrow combined with normal content of hematopoietic parenchyma of other skeleton sites was observed.
The period of time passed after radiation injury can be assessed on the basis of morphological characteristics of bone marrow. Under doses at which the hematopoietic form of radiation sickness takes place, the elements of stroma and plasma cells dominate in cellular composition in the first 2-3 weeks of the disease. Later, after 4 weeks, granular lymphocytes appear. Then morphological signs of early recovery can be observed: the number of hematopoietic stem cells and mitosis increase [13].
Using modern immunomorphological methods of staining of bone marrow sections an expert can make a rough estimation of radiation injury severity. Under the doses within "marrow failure" range (1-10 Gy) the number of dying cells is low - an average of 4-5 in a field of view of a microscope. Under higher doses (intestinal and cerebral form of radiation sickness) - cell death exceeds 50% [14].

4. Conclusion

Thus, a lot of questions traditionally asked experts by investigating authorities can be answered on the basis of the assessment of nature and severity of lesions observed on corpse or body of survivor. They are the following:

- Diagnostics of radiation injures and making decision on possibility or impossibility of development of such lesions under conditions specified in a case files;
- Determination of period of time passed after radiation accident and mechanism of radiation injury development in order to reconstruct circumstances of a case;
- Assessment of exposure conditions, intake of radioactive material, levels and rates of external and internal doses, etc.

Within the investigation of radiation accidents biomedical analyses are necessary. They should be performed to ensure objectivity and scientific relevance of expert’s conclusions.

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