

Ensuring radiation safety of medical examinations using thermoluminescent dosimetry

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Abstract. The paper proposes the use of TLD-K thermoluminescent detectors for measuring absorbed doses at the entrance and exit radiation sites of the patient's body during medical diagnostic examinations. The proposed technique is used in dosimetric control of patients during diagnostic examinations and medical personnel working under X-ray control. The use of small-scale thermoluminescent detectors with cover layers of different thicknesses makes it possible to study the topography of dose distribution both in terms of propagation depth and body area.

Keywords: ionizing radiation, medical diagnostic examination, absorbed dose, patient, thermoluminescence, detector

1. Introduction

Given that the use of sources of ionizing radiation (IRS) in medicine creates human dose loads comparable with all other sources of radiation (including natural), their reduction is extremely important. Currently, radiodiagnostics and radiotherapy are one of the most effective, large-scale and dynamically developing branches of healthcare in any country (more than 80% of all diagnoses are established with their help). The development of medical technologies is characterized by multidirectional trends: a decrease in dose due to the improvement of equipment and an increase due to the introduction of new highly informative technologies – computer tomography and interventional (X-ray surgical) procedures. The second trend dominates, and as a result, the doses are growing; the average annual human doses have increased severalfold in recent years worldwide [1, 2].

Medical exposure of patients has several fundamental differences from natural exposure, which requires special approaches to radiation protection of patients. The important considerations include high dose rates created by radiation sources (several orders of magnitude higher than natural dose rates); significant non-uniformity of dose distribution over the depth of the body at the focus site of irradiation and over the irradiation area as a whole; dependence of absorbed doses on irradiation modes, patient weight, etc.; energy dependence of the readings of detectors and different tissues when using X-ray radiation of 30–150 eV. These features create significant difficulties in monitoring and analyzing the dangers of the medical use of IRS. It is generally assumed that patient tissue doses in diagnostic studies are comparable to stochastic radiobiological effects. The degree of biological hazard of exposure (risk assessment) is based on the use of calculated values of effective and equivalent doses in Sv, which can be used only at low dose loads [3–5]. In radiation therapy, the purpose of which is the destruction of malignant neoplasms with large doses of radiation, tissue reactions of neighboring organs are inevitable, and here it is necessary to measure the absorbed doses. Various regulatory documents have different conversion factors for assessing risks in Sv, which creates some confusion and problems for practitioners [5–8] (Absorbed dose: D (Gy), equivalent dose: H (Sv) = $Wr \cdot D$, effective dose: E (Sv) = $Wr \cdot Wt \cdot D$. To assess the impact on the whole body $\sum Wt = 1$). In most cases, the dose from external gamma exposure to the whole body is approximated by the dose equivalent $H_p(10)$, which is measured using individual tissue-equivalent detectors with a cover layer of 10 mm [5–8]. For weakly penetrating radiation exposures, different metrics are introduced: $H_p(007)$ for the skin and $H_p(3)$ for the lens of the eye [8]. For the purposes of radiation protection in radiotherapy, it is important to be able to rigorously measure the absorbed dose in tissues in Gy, as it is the main regulatory measurement. It should be noted that there are only limited

observations of how the dose loads occurring during diagnostic studies of patients (soft X-ray radiation with high energy losses) are distributed to individual organs and along the depth of the body [4, 9, 10]. The use of small thermoluminescent detectors for rigorous dosimetry of patients could make it possible to fill in some gaps in optimizing modes, protection, etc. Reducing the level of exposure by only 10%, which is realistic if the diagnostic procedures are developed based on rigorous dosimetry measurements, would prevent thousands of cancer cases caused by medical exposure.

2. Thermoluminescent radiation dosimetry

The absorbed dose is the main physical quantity that determines the degree of radiation exposure to the environment and humans, which applies to any type of radiation and any irradiated material. However, it should be noted that the absorbed doses of different types of radiation and energies in different materials at the same exposures can vary significantly. To measure the absorbed dose in a certain medium, it is necessary to use materials as radiation detectors that are closest in their physicochemical characteristics to the parameters of the medium in which the absorbed dose is to be measured (Z_{eff} is the effective atomic number of the detector, density); a necessary condition is to ensure electronic equilibrium (Electronic equilibrium is a state in which the absorbed energy in a given volume of the medium is equal to the total kinetic energy of the electrons released by photons in the same volume) in the detection system. The closer the characteristics of the medium and the detector, the more accurate the dosimetry will be [11–13]. The dose (Gy) measured in different human tissues by tissue-equivalent detectors does not require the use of weighting factors for calculating the equivalent dose and corresponds to the dose in Sv. With a significant inhomogeneity of the radiation field, it is necessary to use detectors with the smallest possible dimensions.

The best detectors for determining absorbed dose in the human body would be tissue-based detectors; and several of such generally accepted methods of dosimetry exist. However, the capability and reliability of biological methods are low.

The thermoluminescent method is widely applied in individual dosimetric monitoring due to several clear advantages: thermoluminescent detectors have a good dynamic range of measured doses, are miniature in size and their dimensions can be potentially reduced further, retain information for a long time, provide acceptable measurement accuracy, and are quite easy to use. The most widely used detectors in solid-state thermoluminescent dosimetry are based on LiF [11]. The dose formed in this material is closest to the dose absorbed by the muscle tissue. For a long time, LiF-based detectors dominated the market for personal dosimetric monitoring (PDM) almost completely. At present, new highly sensitive materials have appeared, which made it possible to reduce the size of the detectors [11]. In this work, we used TLD-K detectors based on silicon oxide, which are cheaper, less toxic and hygroscopic, more sensitive to radiation, and are comparable in their properties to the densest tissues of the human body (bone tissue). In the energy range from 30 to 150 keV, these detectors are characterized by the dependence of the absorbed dose on the radiation energy, which can give a maximum overestimation of the dose to muscle tissue by a factor of 4 (Fig.1) and accurately determine the dose in bone tissue with penetrating radiation.

The use of tissue-equivalent phantoms and a set of tissue-equivalent (with different Z_{eff} for different tissues) miniature detectors is the best way to study the absorbed dose distribution over the irradiated patient's body. The absorbed dose measured in this way in a certain place of the phantom (tissue) will fully correspond to the calculated equivalent dose, which is recommended to be given in Sv because the quality of the radiation (type of radiation) is fully account for when measuring the absorbed dose with tissue-equivalent detectors. In this study, we are testing a simple method for assessing the doses absorbed by a patient using TLD-K detectors both in terms of body depth and area, taking into account the impact on the most vulnerable organs (gonads and thyroid gland).

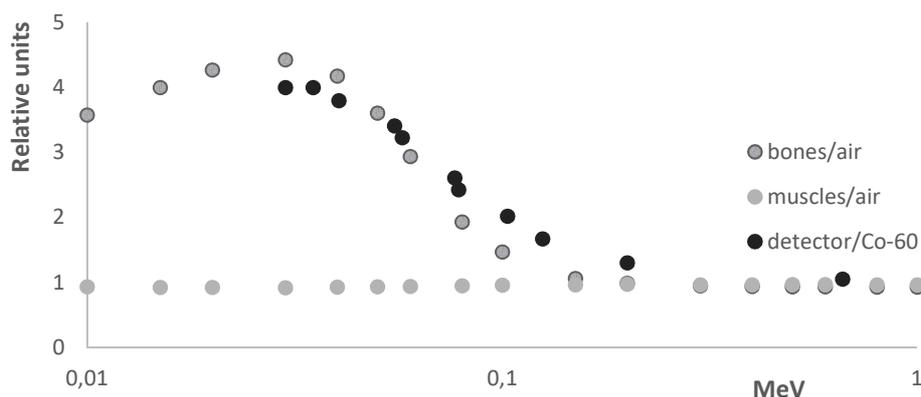


Fig.1. Energy dependence for bone, muscle tissue (ratio of absorbed dose to exposure dose) and detector TLD-K (relative to the readings during irradiation with Co_{60}).

3. Research results

3.1. Methods information

To carry out dosimetric control, TLD-K thermoluminescent detectors based on SiO_2 (chips 3×3 mm, thickness 0.5 mm) were used [11, 12].

The following advantages should be emphasized: the wide dynamic range of measured doses; the small size of the detectors; the high homogeneity of the TLD-K detector batch, which cuts off the need for preliminary selection of detectors in terms of sensitivity, and, consequently, ensures high reliability of dose determination; as well as low cost.

Dosimetric control was carried out in several city clinics of Kuzbass. Clinics used different equipment for X-ray examinations (RUM-20M, Renex fluorograph, ProScan digital fluorographic complex with a wide range of diagnostic functions). In dentistry, EVOLUTION-X3000-2C/1 and ORTHOPHOS XG 3 orthopantomograph [14, 15] were used. Several measurements were taken in a Moscow clinic during surgical operations (coronary catheterization, stenting) under X-ray control.

The reading of information was carried out on the device DTU-01M. Detectors were used in standard dosimetric cassettes made of polyethylene with a front wall thickness of 10 mm with a translucent copper filter, and in aluminum foil with a thickness of 0.1 mm. It should be noted that the detectors in the foil were completely transparent to X-rays and did not show up in the image at all.

Dosimetry was carried out directly during the medical evaluation procedures performed on patients, which provided realistic rather than model conditions for the procedure during the work of personnel.

Dosimeters and assemblies were attached to the patient's skin at the following points:

- entrance – irradiation zone (from the irradiation side),
- exit – irradiation zone (opposite side of the body),
- in the area of the thyroid gland,
- in the area of the gonads.

Therefore, the use of detectors 0.5 mm thick in a dosimetric cassette (10 mm) and aluminum foil (0.1 mm) made it possible to carry out measurements at depths of 0.1–0.6 mm and 10–10.5 mm (entrance), 250.01–250.06 mm and 260–260.5mm (exit). The thickness of the body layer was taken on average as 250 mm.

Dose measurements were taken after each procedure conducted during each patient's medical evaluation. For statistical processing, doses were averaged during dosimetry of at least 6 different patients during identical procedures (modes, frontal projection – PZ, back – ZP or lateral – B). Dosimetry was performed during one of the following medical studies: rib cage, abdomen, lumbar.

In dental radiography, only foil detectors were used for dosimetry, which were located in the areas of the irradiated tooth, frontal lobe, gonads, and thyroid gland.

In addition, individual dosimetric monitoring of personnel was carried out in X-ray work rooms and treatment rooms in various medical institutions.

3.2. The results of determining the dose loads of medical personnel

When measuring the radiation background in Kemerovo using bone and soil equivalent TLD-K detectors, the values range on average from 0.28 to 0.34 cGy/year. In the premises of hospitals, the background measured by dosimeters with TLD-K detectors was 3 ± 0.2 mGy/year. The background in the treatment rooms and the X-ray room turned out to be higher, with the individual doses of the staff averaged 4 mGy/year. Thus, occupational doses of personnel are not high (≤ 1 mGy/year). The minimum average dose of additional exposure of personnel compared to the natural background effect on muscle tissue can be 0.25 mGy/year, and the maximum (bone tissue when exposed to penetrating radiation) 1 mGy/year. Consequently, modern X-ray rooms provide good protection of personnel from exposure.

3.3. The results of determining dose loads on patients in X-ray diagnostics

Fig.2 shows the results of dosimetry during abdominal radiography in the anteroposterior projection, averaged over 10 images of patients performed by different medical staff on different days.

The details of the doses shown on the graph are as follows.

- Entry and exit are doses in the irradiation field, averaged over the layer of human muscle tissue at a depth of 0.1–0.6 mm, 10–10.5 mm and 250.1–250.6, 260–260.5 mm.
- Doses to the gonads and thyroid gland were determined only in the 0.1–0.6 mm layer, with foil detectors attached to the organ location area.
- The doses measured by the TLD-K detectors are reduced by a factor of 4 due to the maximum possible excess of doses on muscle tissue compared to bone tissue (Fig.1), thus representing the lowest possible doses.

The doses to the gonads during examination of the abdominal cavity with the use of protection are small, but without the use of protection (one emergency case) are practically comparable to the input dose, i.e., the gonads are exposed to the radiation field, so the physical protection of the gonads during the examination of the abdominal cavity is extremely important.

In Fig.3. the change in the absorbed dose is given for 4 points of experimental measurements at different depths in the radiation field.

The surface dose at the entrance to the body during the diagnosis of the abdominal cavity drops by a factor of e at a depth of 80 mm to a value of 10 mGy. The maximum dose on the body surface was 30 mGy, which is comparable with the results of studies by other authors [4, 9, 14]. Calculation of risk (equivalent exposure doses) on the basis of the recommended calculation procedures according to the MUK gives a dose of 2.5 mSv, and on the basis of DOS-3 1.5 mSv [8]. Fig.3 shows the average doses measured during examinations of the lumbar region in the ZP and B projections and the distribution of doses over the depth of the body in the radiation field.

Calculation of exposure doses on the basis of MUK amounted to 2.5 mSv and 37 mSv, respectively, and on the basis of DOS-3 0.7 mSv. The entrance dose during diagnostics in the PZ projection drops by a factor of e at a depth of 60 mm to 10 mGy, and in the B projection at a depth of 50 mm to 100 mGy, which is 100 times higher than the DOS-3 estimate. Entrance doses during surveys cannot be attributed to stochastic effects because they exceed the maximum allowable concentrations for personnel.

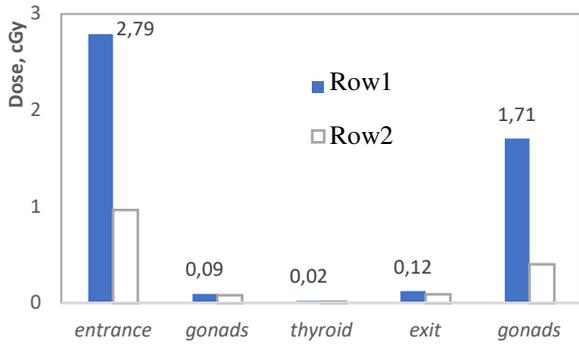


Fig.2a. Dosimetry of patients during diagnostic examination of the abdominal cavity. The minimum absorbed doses are given in terms of muscle tissue. Row 1 is the mean, row 2 is the standard deviation.

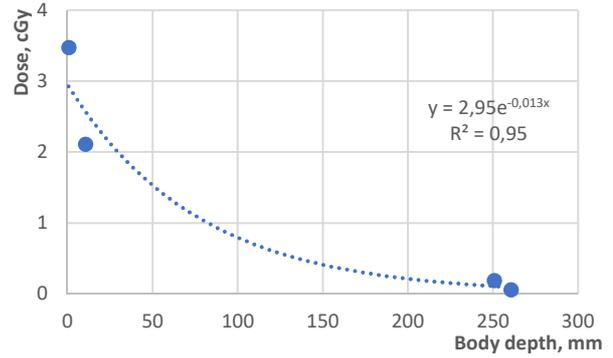


Fig.2b. Dose distribution over body depth in the radiation field. $D = D_0 e^{-\mu d}$, where $\mu (Z, E, \rho)$ is the attenuation coefficient, d is the depth of the body at which the dose drops by a factor of 2.72.

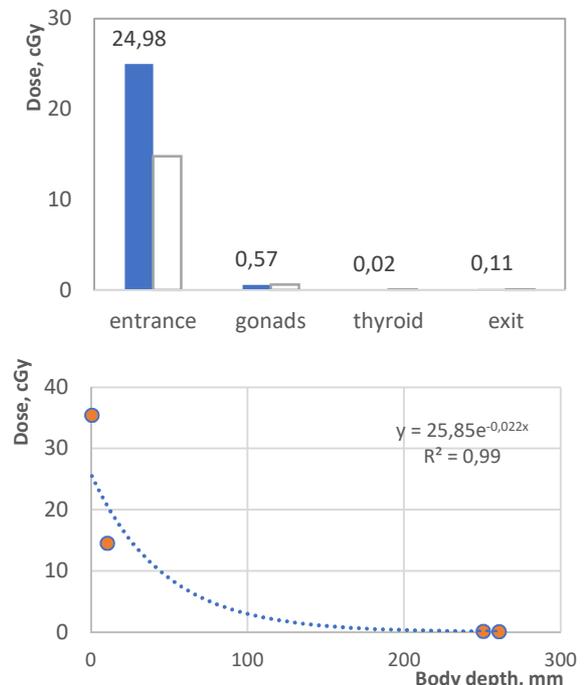
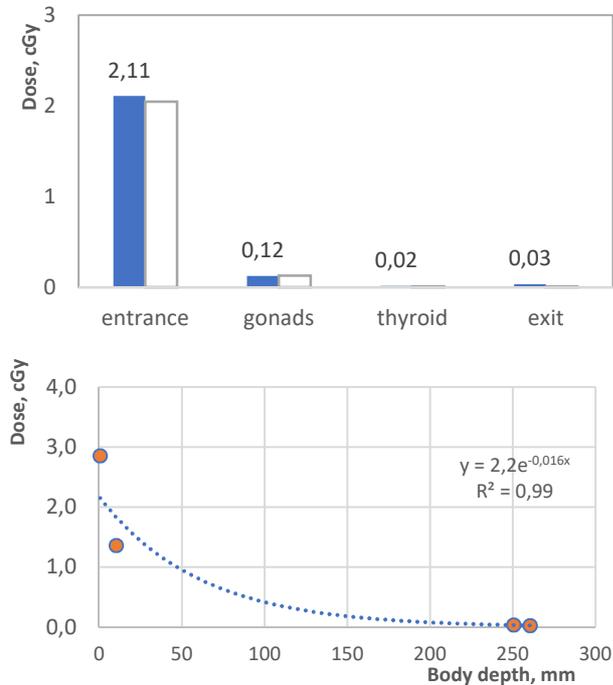


Fig.3. Average absorbed doses per muscle tissue during examinations of the lumbar region in the LR and B projections and the distribution of doses over the depth of the body in the radiation field.

The following figures show the results of dosimetry when examining the chest in the AP projection, using different diagnostic devices.

Input doses when using different devices vary by more than a factor of 10, from 0.4 mGy to 6 mGy. Calculations for MUK give risks of approximately 0.5 mSv, and for DOS-3 0.05 mSv. Surface doses fall by a factor of e at depths from 80 mm to 100 mm and range from 0.2 to 2 mGy (Fig.5). The use of low-dose digital fluorographs makes it possible to reduce the dose load on patients by a factor of 10.

It should be noted that the dose to the bone tissue when shooting the chest in the ZP projection (deepening approximately 30–50 mm) will be twice the input dose (the recorded value at the depth of the bone tissue must be increased by a factor of 4). Therefore, during chest X-ray studies, bone tissues receive the highest radiation dose of all tissues.

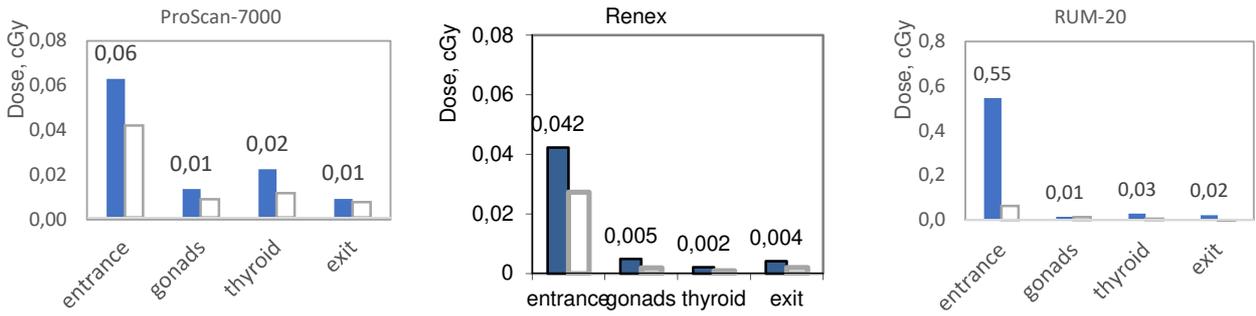


Fig.4. Mean absorbed doses by muscle tissue of patients during chest examinations using different X-ray machines.

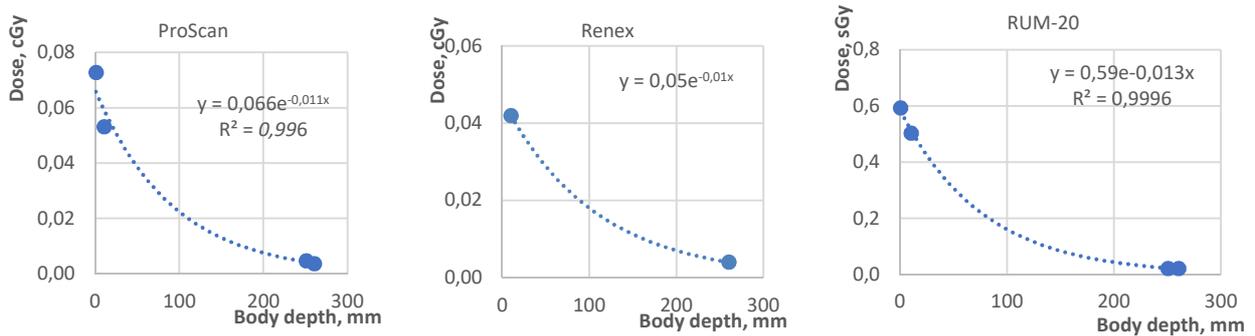


Fig.5. Distribution of tissue doses over the depth of the patient's body in the radiation field during chest examinations using different devices (digital scanning fluorograph ProScan-7000, low-dose digital fluorograph Renex, X-ray diagnostic complex for three workplaces RUM-20M).

The most common type of examination today is x-ray diagnostics in dentistry (tooth x-ray). When X-raying teeth, we estimated the average surface doses in the area of the irradiated tooth (in the diagnosis of different teeth), frontal sinuses, thyroid gland and gonads using the EVOLUTION X 3000-2 C/1 dental X-ray machine and the ORTHOPHOS XG 3 orthopantomograph (Fig.6).

Dose loads on the irradiated tooth during dental radiography are comparable to the input doses on muscle tissue during chest examinations using digital fluorographs. Quite high doses are observed for the frontal bone. The doses in the thyroid gland and gonads are practically the same as in the examination of the chest using the Renex digital fluorograph. It should be noted that preventive examinations for a part of the working population are carried out no more than once a year, and an x-ray of a tooth in the treatment of one pulpitis is often done more than once.

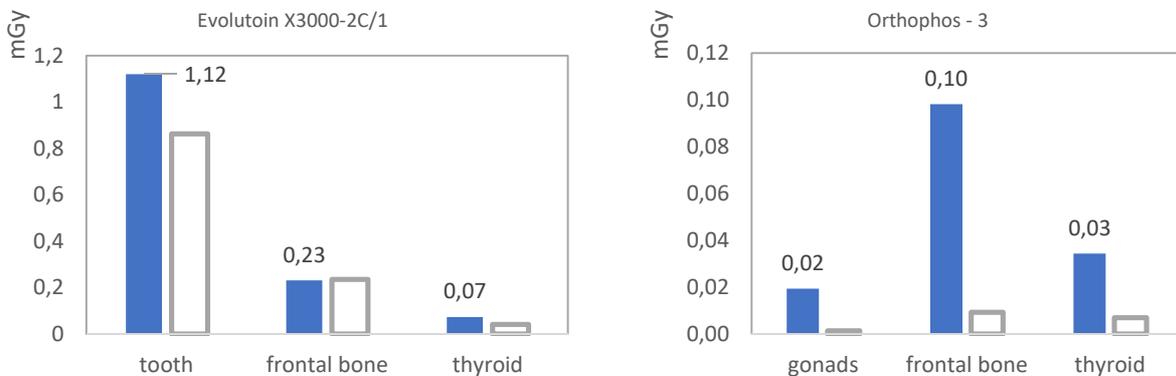


Fig.6. Comparison of surface tissue doses in dental radiography and FG.

3.4. The results of determining dose loads on medical staff during X-ray surgery

Dosimetry was carried out directly during surgical operations performed by medical personnel under X-ray control (coronary catheterization, stenting). Based on the analysis of the results, an assessment of the average dose load on the medical staff for one working day was carried out. When a doctor works ~200 days a year and the average daily absorbed dose per day is ~ 100 μSv , the medical staff receives an annual dose load of 20 mSv, which is the maximum dose for group A professionals. At the same time, the dose on the left hand was approximately 500 μSv . The dose to the patient's thyroid gland was 6 mSv per operation, and the dose to the gonads was 60 μSv , about the same as the average dose to the gonads, thyroid gland and right hand of the medical staff.

4. Conclusion

The doses received by patients, as our studies have shown, can vary greatly between different diagnostic procedures, the same procedure using different x-ray techniques, and even the same procedure performed by different medical personnel, especially for patients with different body weights. Actual doses differ significantly from those recommended in regulatory documents for filling out statistical reports, for example, DOS-3.

The introduction of rigorous dosimetric control of patients, control over the technical condition of X-ray equipment (at least selectively) in realistic conditions of procedures, technical re-equipment of radiation diagnostics, increasing the professionalism of personnel, and the use of modern means of protection can significantly reduce radiation exposure of human population. If we rely on the assessment of medical exposure, according to the recommended modeled data, and do not evaluate the realistic picture, then the reduction in dose loads of the population will not be achieved. In which case, in the near future we might come to an increase in oncological and cardiovascular diseases, a significant increase in the overall morbidity, and weakening of the immunity of our citizens. The probability of spontaneous cancer is $2 \times 10^{-3} \text{ year}^{-1}$. Radiation risks for the population are currently established with a probability of $5 \times 10^{-5} \text{ year}^{-1}$, which corresponds to a background dose of 1 mSv/year. A simple estimate shows that all spontaneous cancers can be due to radiation doses of ~40 mSv. These are the dose loads on patients actually recorded today during certain diagnostic procedures, which could have been even higher in the past, and the doses increase with the use of modern tomographic procedures. Background natural exposure, controlled occupational exposure doses in other branches of science and technology are not comparable with the risks of medical exposure of patients. Increasing the safety of medical diagnostic procedures can significantly reduce the radiation exposure of the human population.

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