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Проблемы облучения персонала в современных медицинских технологиях

С.А. Рыжкин[1, 7], Ю.В. Дружинина[1, 2], З.А. Лантух[2], И.В. Солдатов[2], В.Н. Лесняк[3], Д.П. Лебедев[3], Д.Н. Самочатов[4], М.П. Семенова[5], В.А. Сухов[6], С.Е. Охрименко[1]

[1] Российская медицинская академия непрерывного профессионального образования, Москва, Российская Федерация
[2] Научно-практический клинический центр диагностики и телемедицинских технологий, Москва, Российская Федерация
[3] Федеральный научно-клинический центр специализированных видов медицинской помощи и медицинских технологий, Москва, Российская Федерация
[4] Городская клиническая больница № 67 имени Л.А. Ворохобова, Москва, Российская Федерация
[5] Государственный научный центр Российской Федерации — Федеральный медицинский биофизический центр имени А.И. Бурназяна, Москва, Российская Федерация
[6] Первый Московский государственный медицинский университет имени И.М. Сеченова (Сеченовский Университет), Москва, Российская Федерация
[7] Казанский государственный медицинский университет, Казань, Российская Федерация

АННОТАЦИЯ

Обоснование. Широкое применение источников ионизирующего излучения в медицинской практике (кардиоэндоваскулярной хирургии, эндоскопии, травматологии, урологии, нейрохирургии, стоматологии, отделениях радиоизотопной диагностики) приводит к облучению хрусталика глаза и кожи рук рассеянным излучением низкой интенсивности. Введение МАГАТЭ новых рекомендаций по снижению предела годовой эквивалентной дозы на хрусталик (20 мЗв) привело к тому, что оценка дозы по хрусталику на основе эффективной дозы стала некорректной.

Цель — анализ подходов и оценка эквивалентных доз облучения хрусталика глаза и кожи рук медицинского персонала при проведении различных диагностических исследований под воздействием рентгеновского излучения и гамма-изучения радиофармпрепарата, а также сравнение полученных результатов с ранее опубликованными данными.

Материалы и методы. Применялся метод термолюминесцентной дозиметрии. Оценка доз проводилась у персонала кардиоэндоваскулярной хирургии, эндоскопии, изотопной диагностики, стоматологии, урологии.

Результаты. Расчётные годовые эквивалентные дозы на хрусталик глаза у врачей отделений кардиоэндоваскулярной хирургии находились в диапазоне от 35 до 90 мЗв, среднего медицинского персонала — от 6 до 19 мЗв (в отдельных случаях у врача — до 225 мЗв, у медицинской сестры — до 180 мЗв); персонала отделения радиоизотопной диагностики — от 4,5 до 9 мЗв. Годовые расчётные эквивалентные дозы на кожу рук у персонала кардиоэндоваскулярной хирургии составили от 17 до 100 мЗв, а при работе с радиофармпрепаратами — от 24 до 220 мЗв. Показано, что использование оценки усреднённой дозы за одну операцию у врачей кардиоэндоваскулярной хирургии, как правило, неизбежно приводит к превышению эквивалентной дозы на хрусталик глаза через определённое количество операций.

Заключение. При превышении определённого количества операций (от 100 до 200) у врачей кардиоэндоваскулярной хирургии могут формироваться эквивалентные дозы на хрусталик глаза более 20 мЗв в год. Установлено поражение хрусталика глаза при существующих уровнях облучения у врача кардиоэндоваскулярной хирургии. Полученные результаты свидетельствуют о необходимости дальнейших дозиметрических измерений и эпидемиологических исследований, на основании которых могут быть разработаны рекомендации по радиационной защите хрусталика глаза и кожи рук медицинского персонала, осуществляющего работу в поле рассеянного, гамма- и рентгеновского излучения низкой интенсивности.

Ключевые слова: источники ионизирующего излучения; персонал; кардиоэндоваскулярная хирургия; отделение радиоизотопной диагностики; хрусталик глаза; кожа рук; рассеянное излучение низкой интенсивности; годовая эквивалентная доза; термолюминесцентная дозиметрия; профессиональное поведение.

Как цитировать
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Problems of personnel irradiation in modern medical technologies

Sergey A. Ryzhkin[1, 7], Yuliya V. Druzhinina[1, 2], Zoya A. Lantuh[2], Ilya V. Soldatov[2], Viktor N. Lesnyak[3], Dmitriy P. Lebedev[3], Denis N. Samochatov[4], Maria P. Semenova[5], Vitaly A. Sukhov[6], Sergey E. Okhrimenko[1]

[1] Russian Medical Academy of Continuous Professional Education, Moscow, Russian Federation
[2] Research and Practical Clinical Center for Diagnostics and Telemedicine Technologies, Moscow, Russian Federation
[3] Federal Research and Clinical Center of Specialized Medical Care and Medical Technologies, Moscow, Russian Federation
[4] City Clinical Hospital No. 67 named after L.A. Vorokhobov, Moscow, Russian Federation
[5] State Research Center — Burnasyan Federal Medical Biophysical Center, Moscow, Russian Federation
[6] The First Sechenov Moscow State Medical University (Sechenov University), Moscow, Russian Federation
[7] Kazan State Medical University, Kazan, Russian federation

ABSTRACT

BACKGROUND: The widespread use of radiation sources in medical practice (cardio-endovascular surgery, endoscopy, traumatology, urology, neurosurgery, dentistry, and radioisotope diagnostics departments) leads to irradiation of the lens of the eye and the skin of the hands. The introduction of new recommendations by the IAEA to reduce the limit of the annual equivalent dose to the lens (20 mSv) has led to an inaccurate dose assessment based on the effective dose.

AIM: To analyze approaches and assess equivalent doses of irradiation of the lens of the eye and skin of the hands of medical personnel during various diagnostic studies under the influence of X-rays and radiopharmaceuticals studies and to compare the results obtained with previously published data.

MATERIALS AND METHODS: Thermo-luminescent dosimetry was used. Dose assessment was performed by cardio-endovascular surgery, endoscopy, isotope diagnostics, dentistry, and urology personnel.

RESULTS: The estimated annual equivalent doses to the lens of the eye for doctors of cardio-endovascular surgery departments, in most cases, ranging 35–90 mSv, 6–19 mSv for the average medical staff (in some cases, the doctor [≤225 mSv] and the nurse [≤180 mSv]) and 4.5–9 mSv for the staff of the department of radioisotope diagnostics. The annual calculated equivalent doses to the skin of the hands for cardio-endovascular surgery personnel were 17–100 and 24–220 mSv for the staff working with radiopharmaceuticals. It is shown that the use of an estimate of the average dose per operation by cardio-endovascular surgery doctors, as a rule, inevitably leads to an excess of the equivalent dose to the lens of the eye after a certain number of operations.

CONCLUSION: When a certain number of operations are exceeded (100–200), equivalent doses to the eye's lens in cardio-endovascular surgery doctors above 20 mSv per year can be formed. At current radiation levels, a lesion of the eye's lens was found in a cardio-endovascular surgery doctor. The results indicate the need for further dosimetric measurements and epidemiological studies, based on which recommendations for radiation protection of the eye's lens and the skin of the hands of medical personnel working in low-intensity, scattered, gamma X-ray radiation can be developed.

Keywords: annual equivalent dose; cardio-endovascular surgery; eye lens; hand skin; low-intensity scattered radiation; professional behavior; radiation sources; radioisotope diagnostics department; staff; thermo-luminescent dosimetry.

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使用现代医疗技术时医务人员受到辐射的问题

Sergey A. Ryzhkin[1, 7], Yuliya V. Druzhinina[1, 2], Zoya A. Lantuh[2], Ilya V. Soldatov[2], Viktor N. Lesnyak[3], Dmitriy P. Lebedev[3], Denis N. Samochatov[4], Maria P. Semenova[5], Vitaly A. Sukhov[6], Sergey E. Okhrimenko[1]

[1] Russian Medical Academy of Continuous Professional Education, Moscow, Russian Federation
[2] Research and Practical Clinical Center for Diagnostics and Telemedicine Technologies, Moscow, Russian Federation
[3] Federal Research and Clinical Center of Specialized Medical Care and Medical Technologies, Moscow, Russian Federation
[4] City Clinical Hospital No. 67 named after L.A. Vorokhobov, Moscow, Russian Federation
[5] State Research Center — Burnasyan Federal Medical Biophysical Center, Moscow, Russian Federation
[6] The First Sechenov Moscow State Medical University (Sechenov University), Moscow, Russian Federation
[7] Kazan State Medical University, Kazan, Russian federation

简评

论证。电离辐射源在医疗实践（心血管内外科、内窥镜检查、创伤科、泌尿科、神经外科、牙科、放射性同位素诊断部门）中的广泛使用导致眼球晶状体和手部皮肤受到低强度散射辐射。国际原子能机构引入的关于减少晶状体的年度等效剂量限制（20毫西弗）的新建议导致基于有效剂量的晶状体剂量评估是不正确的。

该研究的目的是分析方法和评估医务人员在X射线辐射和放射性药物的伽马射线影响下进行各种诊断检查时眼球晶状体和手部皮肤的等效辐射剂量，并对所得结果与以前公布的数据进行比较。

材料和方法。采用了热释光剂量测定法。评估了心血管内外科、内窥镜、同位素诊断、牙科和泌尿科人员的剂量。

结果。心血管外科医生眼球晶状体的计算年度等效剂量为35至90毫西弗，护理人员的为6至19毫西弗（在某些情况下，医生的高达225毫西弗，护士的高达180毫西弗），放射性同位素诊断部门人员的为4.5至9毫西弗。心血管内外科人员手部皮肤的计算年度等效剂量为17至100毫西弗，而在使用放射性药物的工作中，则为24至220毫西弗。事实证明，使用心脑血管外科医生每次手术时的平均剂量估算，通常不可避免地会在一定数量的手术后导致晶状体的超标等效剂量。

结论。超过一定数量的手术（100至200），心血管内外科医生每年接受的眼球晶状体的等效剂量可能超过20毫西弗。在现有辐射水平下，心血管内外科医生眼球晶状体的病变已经是确定的。所得结果证明，有必要进行进一步的剂量测定和流行病学调查，在此基础上可以制定在散射、伽马和X射线的低强度辐射影响下工作的医务人员的眼球晶状体和手部皮肤的辐射防护建议。

关键词：电离辐射源；工作人员；心血管内外科；放射性同位素诊断部门；眼球晶状体；手部皮肤；低强度散射辐射；年度等效剂量；热释光剂量测定法；职业行为。

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BACKGROUND

Sources of ionizing radiation are widely used in the current clinical practice. When they are used, sources of ionizing radiation can affect medical personnel of cardioendovascular surgery (CEVS), traumatology, urology, neurosurgery, dentistry, general surgery, and intensive care departments.

In the departments of nuclear diagnostics, the highest radiation exposure is on nurses who prepare and administer radiopharmaceuticals and radiology technicians who examine patients using gamma cameras and single-photon emission computed tomography (CT) or positron emission tomography combined with computed tomography (PET/CT). In these cases, medical personnel are exposed directly and permanently to low-intensity scattered gamma and X-ray radiation. Their eyes and skin are affected by radiation scattered by the patient's body and reflected from external objects. Based on the available data, the ratio of an equivalent lens dose to the effective dose can be calculated in the photon radiation energy range of 0.01–10 MeV. In the range of gamma radiation energies of 0.06–10 MeV, the equivalent lens dose numerically exceeds the effective dose by approximately 20%, whereas in the range of <0.05 MeV, this increase ranges from several times to several dozen times.

Therefore, the basic effective dose limit no longer ensures compliance with the dose limit when the eye lens is irradiated. While strong penetrating types of radiation make the main contribution to the effective dose, weak penetrating radiation (beta particles, photons with energies of <15 keV) provide the maximum doses in the sensitive layer of the skin and eye lens [1,2]. This issue attracted special attention after relevant publications of the International Commission on Radiological Protection and the International Atomic Energy Agency, which supported recommendations to reduce the equivalent dose limit for the lens from 150 to 20 mSv annually and optimize the radiation protection of personnel, considering the "as low as reasonably achievable" principle [3-9].

This study aimed to evaluate the equivalent radiation doses for the eye lens and hand skin of medical personnel in diagnostic examinations using X-ray radiation and gamma radiation of radiopharmaceuticals and compare these results with previously published data on radiation doses for the eye lens and hand skin of medical personnel.

MATERIALS AND METHODS

We have assessed equivalent radiation doses for the eye lens and hand skin of medical personnel exposed to X-ray and gamma radiation of radiopharmaceuticals. A thermoluminescent dosimetry (TLD) method was used to estimate doses. Personal dose equivalent Hp(3) dosimeters with TLD-1011T (Research and Technology Center "Praktika," Russia) and TLD-100 (USA) detectors were used. Measurement ranged from 30 μSv to 12 Sv for energies of 0.005–10 MeV. Dosimeters were exposed by attaching them to the central part of the frontal surface of the hair cover of the personnel. The calendar exposure time was 3–6 weeks; however, the total number of dosimetry operations was recorded for consideration when assessing and calculating radiation doses.

Detector data were processed using a HARSHAW TLD system 4000 thermoluminescent analyzer (Thermo Scientific Ltd., MA, USA) at the Department of Radiochemistry of the M. V. Lomonosov Moscow State University. After reading the thermoluminescence curve and detector annealing, detectors were individually calibrated in the air using a ^{137}Cs gamma radiation source (Eγ = 661 keV), type Ts2-5. The main measurement error with a confidence probability of 0.95 did not exceed 10%. To assess the contribution of the background radiation, some dosimeters were exposed as controls. In studies conducted in 2014–2021 in Moscow (four CEVS departments of three city hospitals, one department of urology, endoscopy, department of CEVS of the Federal Medical-Biological Agency, medical center, PET center and department of dentistry of a private medical center, and department of nuclear diagnostics of the clinic at Russian Medical Academy of Continuous Professional Education) and Kazan (four departments of CEVS in four healthcare organizations), 61 findings were obtained for the equivalent lens dose, including 46 findings in CEVS personnel (22 physicians, 24 nurses), 2 in endoscopy personnel, 4 in dentistry personnel, 1 in urology personnel, and 8 in nuclear diagnostics personnel (^{99м}Tc and ^{18}F).

Clinical examination of personnel included ophthalmological examination such as visometry (with and without correction), refractometry, biomicroscopy of the bulbar conjunctiva and vitreous body, Norn test, and B-scan of the eye.

The study assessed personal radiation doses not combined into a single statistical set because of the characteristics of the exposure conditions for each patient. Moreover, this allowed us to establish a range of radiation dose levels and factors potentially affecting the dose formation.

RESULTS

Several approaches are employed to investigate equivalent lenses in medical personnel. The first approach is to wear a thermoluminescent dosimeter (fixed in a certain site on the head of the medical personnel) for a predetermined time and measure the personal equivalent lens dose Hp(3) after the wearing period ends. This approach is described in MU 2.6.1.3747-22.[1] Such investigations for

[1] Guidelines MU 2.6.1.3747-22 "Control of personal equivalent doses of external radiation for the lens of the eye in personnel) (approved by the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing on May 17, 2022). Available from: https://base.garant.ru/405781929/.

measuring equivalent lens doses in the personnel of Moscow healthcare institutions were conducted in 2014 for various medical professions in the radiation monitoring laboratory of the Department of Radiochemistry of M. V. Lomonosov Moscow State University. The exposure time of TLD Hp(3) was 1 month. The results are presented in Table 1.

The highest values were recorded in CEVS physicians. However, if full responsibility for the use of personal dosimeters is delegated to personnel, partial loss of information on some dosimetry operations may occur, and this is a weakness of such an approach. Another weakness is related to the unreliability of information about the actual number of operations with dosimeters. Therefore, the dose measurement for certain periods with subsequent annual dose recalculation is not suitable for radiation exposure assessment.

The second approach is to measure the accumulated lens radiation dose for a certain number of operations with individual dosimetry. This approach allowed estimating the average dose for one conditional interventional examination. Depending on the procedure type, interventional examinations are classified into “diagnostic” and “therapeutic.” Diagnostic interventional examinations are typically 20–30 min long and have a total exposure time of approximately 3–7 min. Therapeutic interventional examinations are much longer (their duration depends on the complexity of the operation). In one case, the operation time was 2.5 h, and the high voltage time was 28 min.

Our results are presented in Tables 2–4.

Doses per operation (manipulation) differ significantly both in different technologies and within the same specialty. Special attention is needed to the extremely high dose of CEVS nurse exposure. Important factors appear to include the work methods of the individual specialist (number of images, ratio of image/scopy, etc.), particularly the distance from the main operating surgeon and their assistant or nurse to the direct beam zone. This factor can be defined as “professional behavior.” The estimated annual doses in clinic A ranged from 35 to 90 mSv for CEVS physicians, up to 180 mSv for a nurse, and up to 8 mSv for a nurse in the nuclear diagnostics department.

The results of the lens dose assessment in clinic B are presented in Table 3. The estimated annual equivalent dose for the eye lens in clinic B was 60 mSv in physicians and 6–18 mSv in nurses. For the professional behavior parameter, due to the nature of work, the second nurse (“nurse 2”) usually stays longer and closer to the doctor’s workplace (“operator”) than the first nurse (“nurse 1”).

In clinic C, some features of lens dose formation were observed. The highest dose was recorded in a physician with the least number of operations. The estimated annual doses ranged from 53 to 225 mSv in physicians and approximately 19 mSv in nurses. The measurement results are presented in Table 4.

Some factors were assessed, which could potentially affect the dose formation: the number of “high-dose”

Table 1. Results of Hp(3) measurements and an approximate assessment of an annual equivalent dose for the eye lens (H) in various medical personnel [10,11]

Profession	Number of subjects, *n*	Hp(3), mSv	Annual H, mSv
CpeNurses (work with radiopharmaceuticals, ^{99M}Tc)	2	0,37–0,40	4,4–4,8
Angiographer	6	0,31–2,20	3,7–26,4
Nurses (angiography)	5	0,15–0,42	1,8–5,0
Urologist	1	0,72	8,6
Dentist	4	0,13–0,18	1,6–2,2

Table 2. Equivalent lens doses for physicians and nurses in cardioendovascular surgery, endoscopy, and nuclear diagnostics departments of clinic A [12,13]

Profession	Dose per exposure, mSv	Number of operations with dosimetry	Dose per operation, mSv	Acceptable number of operations annually	Approximate number of operations annually
CEVS nurse	12,6	31	0,4	50	450
CEVS physician 1	1,28	13	0,1	200	350
CEVS physician 2	1,69	20	0,085	235	450
CEVS physician 3	1,05	5	0,2	100	450
Endoscopic physician	2,82	58	0,05	400	380
Endoscopic nurse	2,79	58	0,05	400	380
Nurse ^{99M}Tc	0,7	134*	0,005	4000	1600

Note. * Patients.

Table 3. Equivalent lens doses for physicians and nurses in the cardioendovascular department of clinic B

Profession	Dose per exposure, mSv	Number of operations with dosimetry	Dose per operation, mSv	Acceptable number of operations annually	Approximate number of operations annually
Physician	5,7	64	0,1	200	600
Nurse 1	1,5	68	0,02	1000	300
Nurse 2	2,4	41	0,06	340	300

Table 4. Equivalent lens doses for physicians and nurses in the cardioendovascular department of clinic C

Profession	Dose per exposure, mSv	Number of operations with dosimetry	Dose per operation, mSv	Acceptable number of operations annually	Approximate number of operations annually
Physician 12	3,86	35	0,11	180	750
Physician 16	3,5	51	0,07	285	750
Physician 18	3,4	12	0,3	>70	750
Nurse	1,74	68	0,025	800	750

operations, ratio of operator-assistant functions, cumulative dose during operations, and height of the operator (Table 5). The table shows that none of the above factors has a direct effect on dosimetry results. Obviously, the most important exposure factors include not only the number of operations but also their specificity and "professional behavior," which determine the distance from the workplace of the "operator" to the tube. In this context, anthropometric characteristics (e.g., height) can be relevant because they affect the location of personnel relative to the direct beam zone.

Some attention should be also given to certain limitations of available collective protective equipment and the lack of personal eye protection in many organizations. Stationary protective equipment is clearly insufficient because of a narrow hanging screen and the absence or inappropriateness of hanging transparent screens. The use of such equipment could significantly reduce the requirements for the protective properties of personal protective equipment (e.g., 0.15 mm Pb for body protection and 0.1 mm Pb for eyes). Such an approach could generally improve the working conditions for medical personnel.

The equivalent lens doses for medical personnel in various nuclear diagnostics departments were compared with data on the personnel dose load in the diagnostic laboratory of the PET center. A study [14] evaluated the equivalent lens doses in medical personnel of the PET center working with ^{18}F-based products, including workload assessment for personnel working with ^{18}F (Table 6).

The equivalent effective dose for nuclear diagnostics personnel of the PET center ranged from 4.2 to 4.9 μSv/GBq (4.2–4.9 μSv/patient) during injection/packing operations and 6 μSv/GBq (2.3 μSv/patient) in a PET/CT technician,

Table 5. Factors potentially affecting radiation dose formation

Physician	Ratio of operation number and dose per patient >1 Gy/>2 Gy	Cumulative dose, Gy	Ratio operator/assistant	Height, cm
Physician 12	19/5	39	24/11	183
Physician 16	17/5	49	29/22	185
Physician 18	3/1	9,4	12/0	170

Table 6. Lens radiation doses (H_{lens}) and effective dose (E) in diagnostic laboratory personnel of the diagnostic laboratory of the PET center depending on the radiopharmaceutical activity and number of patients. [14]

Specialist	Operations	A, GBq	Number of patients	H_{lens}, mSv Hp(3)	E, mSv Hp(10)
A	Nurse, more administration than packing operations	109,2	283	0,63	0,53
B	Packer, more packing than administration operations	124,5	324	0,67	0,52
C	PET/CT technician, scan	135,2	354	0,8	0,81

Note. PET/CT, positron emission tomography/computed tomography.

according to the equivalent lens dose of 5.4–5.8 μSv/GBq (2.1–2.2 μSv/patient) and 5.9 μSv/GBq (2.3 μSv/patient), respectively. The exposure level was directly dependent on the total activity used (or the number of patients as an "equivalent" of activity). The evaluation of the dose–activity/dose–patient relationship makes it possible to calculate the minimum number of required staff. For packing/administration operations, the largest dose load is associated with the "administration" operation, which is the main dose-forming factor for this technology. Considering the workload, the highest lens radiation dose was reported in PET/CT technicians. This can be explained by his/her contact with all activities, whereas the nurse and packer "share" this activity. Values of Hp(10) and Hp(3) doses were nearly close when working with radiopharmaceuticals. Preliminary estimates of the annual equivalent lens doses for 11 months (excluding holidays) are presented in Table 7.

The highest dose is reported in a CT technician. However, he/she showed extremely cautious "working behavior" (keeping the maximum distance and minimizing contact). The staff workload was 26 patients per 14-h shift. With workload intensification (excluding a rather lengthy registration procedure), the dose load also increased proportionally. In the absence of activity distribution between personnel (a and b), the equivalent lens dose can be at least 15 mSv annually. Data obtained are consistent with previous data [15,16], in which the median and maximum values ranged from 4 to 14 and from 6 to 23 mSv, respectively. The ratio of the patient number and staff number is an important factor in determining the levels of exposure in nurses in nuclear diagnostic departments using specific technologies.

In addition to the lens dose assessment, hand skin exposure doses were assessed for the staff of the CEVS and nuclear diagnostics departments. Results are presented in Table 8. As shown in this table, equivalent doses in the above studies do not exceed the limit of the equivalent dose for the skin (500 mSv). These measurements characterize a separate local skin site (usually the back of the middle finger) and cannot fully characterize doses over the entire hand (both the back and palmar surface). Authors are aware of two cases of visible abnormal hand skin changes in CVES physicians, including permanent local foci of dry dermatitis in the palmar-outer edge of both hands and redness in backhand surfaces after surgery.

For this paper, the authors investigated skin radiation doses using hand phantoms for CVES surgeons. Obtained data indicate the possibility of hand skin exposure at the level of ⩾1 Gy annually [13]. The estimated annual equivalent skin doses for nuclear diagnostics personnel of the PET center for 11 working months are presented in Table 9 [15].

The largest contribution to the nurse skin dose load is the administration of a radiopharmaceutical to a patient. The distribution of the dose load between nurse 1 and the "packer" (or nurse 2) deserves special attention. If nurse 1 performs all (100%) injections, the equivalent hand skin dose can be approximately 450 mSv annually. The given data are

Table 7. Estimated annual equivalent lens doses in isotope laboratory personnel of the PET center. [12,14]

Personnel	Function	H, mSv annually
A	Administration ~60%, packing 40%	6,9
B	Packing ~60%, administration 40%	7,4
C	PET/CT technician	8,8

Note. PET/CT: positron emission tomography/computed tomography.

Table 8. Estimated annual equivalent hand skin doses in cardioendovascular surgery. [12,14]

Personnel	H_{skin**} per exposure, mSv	Number of operations	Number of operations annually	H_{skin} annual/estimated
CEVS nurse	1,2	31	450	17
CEVS physician 1	0,7	13	350	19
CEVS physician 2	4,5	20	450	100
CEVS physician 3	1,1	5	450	100

Note. CEVS, cardioendovascular surgery.

Table 9. Estimated annual equivalent skin doses (Hp, 0.07) for fingers (middle finger) in isotope laboratory personnel of the PET center

Personnel	Function	Hp (0.07), mSv annually
a	Administration ~60%, packing 40%	220
b	Packing ~60%, administration 40%	132
c	PET/CT technician	24

Note. PET/CT: positron emission tomography/computed tomography.

well comparable with work indicators [17] ranging from 3 to 512 mSv.

To clarify these data, equivalent skin doses were assessed using hand phantoms of CVES personnel. Equivalent doses for hand phantoms for one operation ranged from 0.5 to 2.5 mSv, with an average input dose of 500 mGy per patient body phantom. Considering the total number of operations per year for a particular surgeon (300–600 operations), equivalent doses for local hand skin sites may exceed the established dose limit of 500 mSv. In the study of DNA double-strand breaks in skin fibroblasts irradiated in parallel with dosimeters, the number of γH2AX and 53BP1 foci at 30 min and up to 24 h after irradiation statistically significantly (p <0.05) exceeded the control values by >2 times, and even after 72 h, indicators did not decrease to control values [13,18].

DISCUSSION

This problem has a long history of scientific discussion [19–24]. Equivalent lens and skin doses were assessed in interventional examinations per single operation. Lens doses ranged from 0.05 to 0.4 mSv. Hand skin doses ranged from 0.3 to 1.1 mSv. Data scatter is up to approximately eight times for the eye lens and up to four times for the hands. In a previous study [19], the skin dose was equal to the lens dose per operation. Equivalent lens doses per operation in interventional procedures have ranged significantly depending on the type of procedure and presence or absence of personal or collective protective equipment [2]. Owing to the significant uncertainty of available data, lens radiation doses still require further evaluation. In a previous study [25], an increased prevalence of cataracts was reported in medical personnel exposed to ionizing radiation, with a higher prevalence in CVES personnel.

In a 17-month study, three radiologists performed pediatric and adult interventions. For 1 year, 276–338 procedures were performed, and 20% of them were in pediatrics. The annual doses for the left eye exceeded 20 mSv and ranged from 21 to 61 mSv. Despite eye protection by special goggles, doses exceeded 6 mSv and ranged from 13 to 48 mSv for both eyes. No significant differences were found in lens doses per procedure between pediatric and adult interventions [26].

When studying the lens dose load in nine interventional radiologists, the equivalent doses for the eye lens and neck skin were evaluated for 6 months. The lens doses were 0.18 ± 0.11 mSv and 35.3 ± 6.6 mSv per working day and 200 working days, respectively. In 5 (56%) CVES physicians, the dose exceeded the annual limit (20 mSv). Studies have concluded that full-time CVES physicians may suffer from the deterministic effects of lens radiation, particularly on the left side. A study also reported the possibility of estimating lens radiation doses according to neck skin dosimetry data [D_{lens} = 0.0179 + (0.5971 × D_{neck})] [27].

Results of the study with 44 CVES physicians and 22 controls are presented. Of the total number of examined participants, 26 CVES physicians and controls underwent a special eye examination. Lens doses were measured by thermoluminescent dosimetry. The average equivalent doses in surgeons were 0.83 ± 0.59 and 0.35 ± 0.38 mSv per month for the left and right eyes, respectively, and annual doses were approximately 0.7–11 mSv. No significant differences in the prevalence of nuclear or cortical lens opacities were noted between groups. Four CVES physicians had early-stage subcapsular sclerosis, although no statistical differences were noted between groups. Based on these data, a study concluded the possibility of significant lens doses in CVES physicians and recommended using eye protection [28].

A study [29] enrolled 69 interventional cardiologists and 78 controls who were not professionally exposed to ionizing radiation. Lens opacities were examined using a slit camera. Cumulative lens doses were assessed retrospectively using a questionnaire including occupational history and lens doses. The average cumulative lens doses for the left and right eyes were 224 S and 85 mSv, respectively. Nuclear opalescence and opacification of the lens nucleus in the left eye were found in 47% of CVES physicians and 42% of controls, cortical opacities were found in 25% and 29%, and posterior subcapsular opacities were found in 7% and 6%, respectively. A statistically significant increase was found in the risk of opacity in the CVES group compared with the control group after adjusting for age, sex, smoking status, and medical exposure. However, no significant increase in cataract incidence was found when compared with controls, including the lack of evidence on the increased risk of opacity with increasing doses. The authors cannot rule out the adverse effects of ionizing radiation because of the relatively small sample size.

In a study assessing doses to the personnel of St. Petersburg healthcare institutions, the following equivalent lens doses were found for 3 months of exposure: for radiologists, 0.29–2.9 mSv per month; CVES physicians and nurses, 0.44–1.49 mSv; radiologists, 0.1–8.54 mSv; surgeons, 0.89 mSv; surgical nurses, 0.11–4.6 mSv. Levels of lens radiation were assessed based on the estimated ratio of personal dose equivalents Hp(3) and Hp(10). Based on the annual Hp(3) and Hp(10) values with the approximation of the log-normal distribution, the probability rates of exceeding 1, 6, and 20 mSv were 13%, 10%, and <1%, respectively. Moreover, considering that interventional radiology teams are the most exposed group in medicine, the percentage of cases exceeding 20 mSv annually can be up to 10%, and lens damage can be stochastic (random) [30,31]. These results differ significantly from results obtained in the European project Optimization of Radiation Protection Medical Staff [32-34] assessing lens radiation doses in interventional specialists from >30 European medical centers. In nearly 50% of CVES physicians, the radiation lens dose exceeded 20 mSv annually.

However, the chronic exposure effect on cataract development was noted in a cohort of the Mayak Production

Association specialists, where 15,000 people exposed to gamma radiation at doses of <0.25 to >1 Gy, showed a statistically significant linear association between the incidence of senile cataracts and the total dose of external gamma radiation. More studies have also shown the increased risk of all types of cataracts, including posterior cortical, nuclear, and subcapsular cataracts in chronically exposed workers. Cataract risk was significantly higher in women [35]. As a result of a radiation accident in Southern Urals, population doses ranged up to 5 mSv in 793 people, 5–100 mSv in 517, and >100 mSv in 67. These data were obtained for a long period after exposure. Studies have shown a significant effect of radiation dose. Opacities in the lens nucleus and posterior capsule developed [36].

Personnel are also chronically exposed to healthcare technologies. According to Kazan data [37], equivalent lens doses in 11 CVES physicians and 15 CVES nurses ranged from <2 to 16.92 mSv for 3 months. In 7 of 21 physicians, equivalent lens doses exceeded or were close to 20 mSv annually. During a clinical examination, 5 of 7 physicians aged 30–70 years had hyperechoic lesions in the vitreous cavity without age-related vascular changes. Some changes were typical for the dry eye syndrome (complaints of eye discomfort, scanty mucous discharge from the conjunctival cavity, eye redness in the evening, eye floaters in the left eye, itching, foreign body sensation, a fold of the conjunctiva outside the limbus, and tear stream thinning) and a decrease in tear film rupture time during the Norn test. In 4 of 5 participants, a superficial injection of the bulbar conjunctiva was detected, and 1 physician had conjunctiva pigmentation. In 2 physicians (45 and 70 years old), an arcus senilis was detected, which is described in the literature as a corneal change typical for older people (according to the World Health Organization, older people are those aged ≥60 years). A clinical examination showed the following abnormal eye changes in one CVES physician (34 years old, annual equivalent lens dose 18.7 mSv): conjunctival damage, dry eye syndrome, damage (destruction) of the vitreous body, and lens nucleus compaction. Changes observed may be associated with exposure to sources of ionizing radiation. The possibility of abnormal processes after low-dose exposure, caused by oxidative stress and the release of free radicals, was also reported [38,39].

Study Limitations

The study is limited by the study interval of one to several months, collection of data on radiation exposure of healthcare personnel, and limited number of participating organizations for data collection.

CONCLUSION

In all cases, considering the number of operations performed, the estimated annual equivalent doses for the eye lens in CVES physicians exceeded the level of 20 mSv and ranged from 35 to 90 mSv. Nurse doses ranged from 6 to 19 mSv. In two cases, the estimated lens dose was >150 mSv (nurse in clinic A: 185 mSv; "operator" of clinic C, 225 mSv).

The lens dose limit is achieved in CVES physicians when performing >200 operations and sometimes <70 operations and <50 operations in CVES nurses.

The distance from the workplace to the X-ray beam zone is the leading factor of radiation dose formation in CVES. This factor is partially associated with the professional behavior of the personnel. Based on the available data, we can assume the stochastic nature of eye damage in the studied dose range. Exposure may be manifested by abnormalities at a younger age than in non-exposed individuals, even in the absence of statistical differences with comparison groups. The hand skin doses of various personnel can come close to and even exceed the normalized annual limit (500 mSv) by ≥2 times.

At present, in addition to monitoring the exposure levels for individual organs and tissues in personnel using state-of-art medical technologies, epidemiological studies are needed, and practical recommendations must be developed for personnel protection using personal and collective protective equipment, with consideration of factors that affect the radiation dose.

ADDITIONAL INFORMATION

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AUTHORS' INFO

*** Yuliya V. Druzhinina;**
address: 24/1 Petrovka street, 127051 Moscow, Russia;
ORCID: 0000-0002-3230-3722;
eLibrary SPIN: 1973-2848;
e-mail: druzhininaYV2@zdrav.mos.ru

Sergey A. Ryzhkin;
ORCID: 0000-0003-2595-353X;
eLibrary SPIN: 5955-5712;
e-mail: rsa777@inbox.ru

Zoya A. Lantukh;
ORCID: 0000-0001-6623-9610;
eLibrary SPIN: 5486-6496;
e-mail: LantukhZA@zdrav.mos.ru

Ilya V. Soldatov;
ORCID: 0000-0002-4867-0746;
eLibrary SPIN: 4065-6048;
e-mail: SoldatovIV2@zdrav.mos.ru

Viktor N. Lesnyak;
ORCID: 0000-0002-2739-0649;
eLibrary SPIN: 5483-3113;
e-mail: lesnyak_kb83@mail.ru

Dmitriy P. Lebedev;
ORCID: 0000-0003-1551-3127;
eLibrary SPIN: 4770-5722;
e-mail: lebedevdp@gmail.com

Denis N. Samochatov;
ORCID: 0000-0002-5230-2006;
eLibrary SPIN: 3340-2715;
e-mail: dnsamochatov@gmail.com

Maria P. Semenova;
ORCID: 0000-0003-0904-0415;
eLibrary SPIN: 7205-0062;
e-mail: mps-fmbc@yandex.ru

Vitaly A. Sukhov;
ORCID: 0000-0003-2993-0108;
e-mail: cyxowv@gmail.com>

Sergey E. Okhrimenko;
ORCID: 0000-0002-8282-1798;
eLibrary SPIN: 6595-4011;
e-mail: ooniii@mail.ru

ОБ АВТОРАХ

*** Дружинина Юлия Владимировна;**
адрес: Россия, 127051, Москва, ул. Петровка, д. 24, стр. 1;
ORCID: 0000-0002-3230-3722;
eLibrary SPIN: 1973-2848;
e-mail: druzhininaYV2@zdrav.mos.ru

Рыжкин Сергей Александрович;
ORCID: 0000-0003-2595-353X;
eLibrary SPIN: 5955-5712;
e-mail: rsa777@inbox.ru

Лантух Зоя Александровна;
ORCID: 0000-0001-6623-9610;
eLibrary SPIN: 5486-6496;
e-mail: LantukhZA@zdrav.mos.ru

Солдатов Илья Владимирович;
ORCID: 0000-0002-4867-0746;
eLibrary SPIN: 4065-6048;
e-mail: SoldatovIV2@zdrav.mos.ru

Лесняк Виктор Николаевич;
ORCID: 0000-0002-2739-0649;
eLibrary SPIN: 5483-3113;
e-mail: lesnyak_kb83@mail.ru

Лебедев Дмитрий Петрович;
ORCID: 0000-0003-1551-3127;
eLibrary SPIN: 4770-5722;
e-mail: lebedevdp@gmail.com

Самочатов Денис Николаевич;
ORCID: 0000-0002-5230-2006;
eLibrary SPIN: 3340-2715;
e-mail: dnsamochatov@gmail.com

Семенова Мария Петровна;
ORCID: 0000-0003-0904-0415;
eLibrary SPIN: 7205-0062;
e-mail: mps-fmbc@yandex.ru

Сухов Виталий Александрович;
ORCID: 0000-0003-2993-0108;
e-mail: cyxowv@gmail.com>

Охрименко Сергей Евгеньевич;
ORCID: 0000-0002-8282-1798;
eLibrary SPIN: 6595-4011;
e-mail: ooniii@mail.ru

* Corresponding author / Автор, ответственный за переписку