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Estimation of the occupational exposure dose for medical diagnostic X-ray workers in Jiangsu, China, using a retrospective dosimetry method

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ABSTRACT

Medical diagnostic X-ray workers are one occupational group that has exposure to continuous low doses of external radiation over their working lifetimes. Current ICRP recommendations [ICRP. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Ann ICRP* 1991;21 (1–3)] state that there is no threshold of stochastic effects induced by radiation exposure such as carcinogenicity or genetic defects, and that the frequency of the effects is proportional to the amount of exposure to low levels of radiation, which is measured by radiation dose. In order to determine the dose information for this special occupational group over their working lifetimes (focusing particularly on workers exposed before 1985, when there was no personal dose monitoring), a sampling survey of the occupational history for these workers was conducted and an occupational history database was established. Using the database and retrospective dosimetry method of Zhang *et al.* (A retrospective dosimetry method for occupational dose for Chinese medical diagnostic X-ray workers. *Radiat Prot Dosimetry* 1998;77:69–72), the annual occupational exposure dose for medical diagnostic X-ray personnel working between 1950 and 2011 was computerized. Some annual dose results estimated using the proposed method were numerically in good agreement with the monitoring results. The average of the annual dose for these medical workers peaked during the mid-1950s and then declined, reaching very low levels by the 1990s and remaining at those levels thereafter. The trend in the annual dose is similar to that reported by earlier studies by Zielinski *et al.* (Health outcomes of low-dose ionizing radiation exposure among medical workers: a cohort study of the Canadian national dose registry of radiation workers. *Int J Occup Med Environ Health* 2009;**22**:149–56). The dose calculated by the retrospective dosimetry method can truly indicate the degree of the workers' exposure in their medical X-ray diagnostic work.

Keywords: occupational exposure; medical diagnostic X-ray workers; retrospective dosimetry method

INTRODUCTION

With the wide application of ionizing radiation in the field of medicine, human exposure to ionizing radiation has been continuously increasing. On a worldwide scale, medical radiation has become the main source of artificial radiation, as it is responsible for one-fifth of the annual collective effective dose of artificial radiation [1]. In China, the use of diagnostic and therapeutic procedures in radiology and nuclear medicine has increased continuously, with the annual per capita dose doubling over the past two decades [2]. Medical radiation workers (doctors, nurses and other medical staff) who are exposed to low doses of ionizing radiation from a variety of data sources (e.g. from diagnostic X-rays and other medical devices) are the occupational group with the largest exposure to artificial radioactive sources [1].

In the Jiangsu province of China, a cohort study of 3961 medical diagnostic X-ray workers with 3742 controls was carried out for ~30 years in order to examine the correlation between occupational radiation in a hospital workplace and different kinds of cancers [3]. The dose information required for further study of the radiation health effects is not yet available.

Prior to 1985 there was a lack of information regarding direct measurement of the personal dose [4], because the national individual dose monitoring system had not been established; however, we can obtain information about the parameters of the medical X-ray devices, protective procedures, and workloads, through indirect means. Therefore, the purpose of this paper was to determine the dose information for these radiation workers, based on the indirect data.

These radiation workers mainly used radiographic installations and fluoroscopic installations to carry out radiological diagnosis. Only a small number of radiation workers used interventional facilities, mammographic installations, or computed tomography to carry out radiation diagnosis and treatment after the 1980s. During the 1980s, the country had increasingly paid more attention to radiation protection for radiation diagnosis and treatment. Compared with the use of radiographic installations, especially fluoroscopic installations near X-ray sources during the period from the 1950s to the 1970s, doses received by radiation workers using computed tomography or mammographic installations in the compartment conditions were very low. Radiation workers who worked near interventional radiology equipment were exposed to larger radiation doses. This research involved calculating and comparing the dose received by medical diagnostic X-ray workers performing a variety of work (fluoroscopy, radiography or interventional radiology) and using a range of protective protocols, as estimated by their workloads, which are characterized by the number of patients who were diagnosed by a certain type of radiation equipment within a certain period of time. Due to the range in function of the fluoroscopy, the length of time over which medical diagnostic X-ray workers received exposure to radiation varied. In order to obtain more accurate dose results, fluoroscopy was further subdivided into fluoroscopy (excluding group), gastrointestinal radiography, bone reduction under fluoroscopy, and group fluoroscopy, on the basis of earlier studies [5].

MATERIALS AND METHODS

Study population

A sampling survey involving medical diagnostic X-ray workers was conducted in 13 cities of Jiangsu province from 1950 to 2011. We selected workers with the following characteristics: (i) they worked in the Department of Radiology and had the possibility of being exposed to low-level radiation; ii) they were responsible for the operation and maintenance of diagnostic radiology equipment. For eligibility for this cohort study, workers also needed possession of a clear medical record and to be free of any kinds of cancers both at the time of recruitment and within the first 5 years thereafter. When the cohort was first established in 1981, 3919 medical X-ray workers who participated in diagnostic radiology work during the period from 1950 to 1980 were recruited as meeting the above conditions. After the baseline survey, all of the cancer-free participants were encouraged to attend the four follow-up surveys conducted in 1986, 1991, 1996 and 2011. The current paper reports the data collected between 1981 and 2011.

Collection of indirect information

After informed consent was obtained, trained interviewers interviewed the subject, or his colleagues, using a pre-tested standard questionnaire to obtain information on occupational history in radiation, types of radiation work, types and parameters of the medical X-ray equipment used, operating conditions, protective measures taken, workload, and abnormal exposure, etc. Among the subjects, the types of radiation work included radiography, interventional radiology, fluoroscopy (excluding group), gastrointestinal radiography, bone reduction under fluoroscopy, and group fluoroscopy. To make the survey content comprehensive and concise, the investigators also referred to information from the hospital records.

Ethical considerations

This study was approved by the Survey and Behavioral Research Ethics Committee of the Jiangsu Provincial Center for Disease Prevention and Control. The respondents were assured of the security of their information and confidentiality, and they were informed of their right to withdraw from the study at any time. Informed consent was obtained prior to the data collection.

Retrospective dose reconstruction

To a certain extent, the workloads of medical diagnostic X-ray workers represent how much exposure they received, but the workloads are not directly proportional to the amount of exposure. Even with the same workload and similar type of radiation work, the doses received by radiation workers can differ, depending on the radiation protection conditions. However, the workload can be used to estimate the dose, after adjusting according to the above two factors (type of work and protection condition). Indirect information related to the protection conditions includes the operating conditions and the protective measures taken. The modified workload is known as the normalized workload.

$$D_{ij} = \sum_{j} \sum_{k} r_k W_{ijk} \tag{1}$$

D_{ij} is the cumulative skin-absorbed dose of the i th worker from the j th year to June of 2011(in mGy). r_k is the correction coefficient for the skin-absorbed dose from the workload of the i th worker who was exposed to the k th working condition (in mGy per thousand person-time),which refers to an earlier study (Zhang L., 1998). W_{ijk} is the workload of the i th medical diagnostic X-ray worker in the k th working conditions in the j th year (thousand person-time).

Using the above formula, we can calculate the cumulative skin-absorbed dose D_{ij} of the workers. We can also calculate the annual skin-absorbed dose d_{ij} (in Gy), which is the annual skin-absorbed dose of the i th worker in the j th year.

$$d_{ij} = D_{ij} - D_{i(j-1)} \tag{2}$$

Then $H_{\mathrm{p}}(10)_{ij}$ of the i th worker in the j th year can be determined with the following equation:

$$H_p(10)_{ij} = \frac{C_{KP} d_{ij}}{C_{KT}} \tag{3}$$

C_{KT} is the conversion coefficient for the skin-absorbed dose from air kerma free-in-air (in Gy·Gy^{-1}), C_{KP} is the conversion coefficient for $H_p(10)$ from air kerma (in Sv·Gy^{-1}), and C_{KT} and C_{KP} refer to Table A.14 and Table A.24 in the ICRP recommendations [6], respectively.

The following factors need to be considered for the selection of C_{KP} and C_{KT}.

(i) Irradiation geometry (such as antero–posterior, postero–anterior, lateral, isotropic, etc.)

The medical diagnostic X-ray workers are generally oriented toward the patient, whether in compartment conditions or near the X-ray source. Therefore, antero–posterior was chosen for the medical diagnostic X-ray workers as the irradiation geometry.

(ii) Ray energy

In ICRP Report 74, C_{KP} and C_{KT} are given for the monoenergetic photons, not for the X-ray spectrum. The effective energy of the X-ray is equivalent to the spectral dosimetry. An X-ray beam has the same decay rate as a single photon, and the energy of the photon is considered to be the effective energy of the X-ray. In this study, the selection of the X-ray effective energy was based on data from other articles [7].

The average of the annual dose was calculated using the following formula:

$$\bar{H}p(10)_j = \frac{\sum_{i=1}^{n} Hp(10)_{ij}}{\sum_{i=1}^{n} Y_i} \tag{4}$$

Y_i is the duration of the i th worker engaged in radiation work in the j th year (in year), and it can take decimal numbers or fractions from 0 to 1.

Analysis

The data was entered by double-entry and was subject to the consistency test by Epidata 3.02. The occupational exposure dose was calculated using the Visual Basic application on the computer. The program flow diagram is shown in Fig. 1.

RESULTS

Demographic characteristics

Between the years of 1950 and 2011, a total of 3702 medical diagnostic X-ray workers were recruited and followed up. The observed total person-time of participation in the work was 109 288 person-years. In our study, only 259 participants were lost to follow-up, with an overall retention rate of 93.5%. The changing trends in the number of participants over time are shown in Fig. 2.

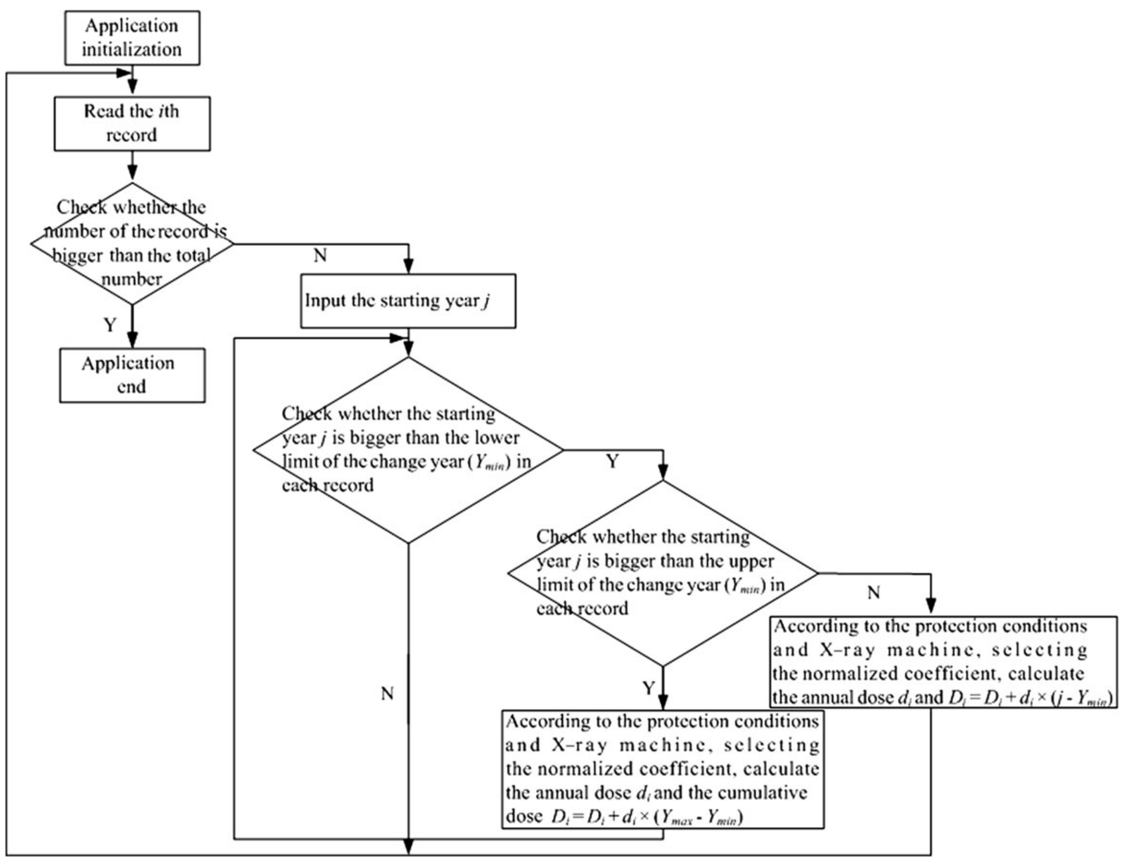

Fig. 1. Flow chart of the computer program.

During the period from 1970 to 1980, ~73.2% of workers participated in radiation work, which can be explained by the evolution of the health care staff in China during that time. After 1970, many hospitals in China started to establish independent radiation departments, and the health workers in the new departments were experienced doctors who had transferred from other departments within the same hospital. The mean age of the participants at the time of recruitment (time of entering the radiation field) was 27.6 ± 6.3 years old. At the end of the follow-up, the mean age of the unexposed group was 66.7 ± 7.3 years old. In the decade before the survey, ~45.3% of workers departed from radiation work, mainly because of retirement. At the end of the follow-up, only 624 workers of the original were engaged in diagnostic radiology work.

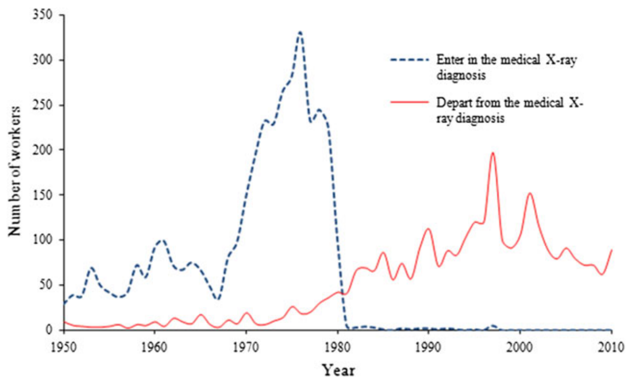

Fig. 2. The trend in the number of medical diagnostic X-ray workers over time.

Radiological diagnostic workload and protective measures

In our study, the workload was the most important indirect information we collected. During the follow-up period, the total workload for radiography, fluoroscopy (excluding group), gastrointestinal radiography, interventional radiology, bone reduction under fluoroscopy, and group fluoroscopy was 226 682 thousand person-time, 388 191 thousand person-time, 70 939 thousand person-time, 386 thousand person-time, 2751 thousand person-time and 195 739 thousand person-time, respectively. The workload and the average annual workload for radiological diagnostic work was distributed among the types of work as shown in Table 1.

Table 1. Distribution of the workload and average of the annual workload for radiological diagnostics as divided by type of work (thousand person-time, thousand person-time per year)

	<1960	1960–1969	1970–1979	1980–1989	1990–1999	2000—
Radiography						
Total workload	6714	15 750	40 201	64 630	56 932	42 455
Average of annual workload	2.0	2.2	2.2	2.4	2.7	3.7
Interventional radiology						
Total workload	0	0	0	77	147	162
Average of annual workload	0	0	0	0.15	0.17	0.20
Fluoroscopy (excluding group)						
Total workload	17 908	39 575	84 960	111 598	83 316	50 834
Average of annual workload	4.7	4.5	3.8	3.7	3.7	3.8
Gastrointestinal radiography						
Total workload	1947	5529	13 863	20 578	17 779	11 243
Average of annual workload	0.57	0.76	0.76	0.80	0.91	0.95
Bone reduction under fluoroscopy						
Total workload	44	167	587	857	700	396
Average of annual workload	0.13	0.14	0.13	0.13	0.13	0.12
Group fluoroscopy						
Total workload	1555	9403	44 425	69 931	47 294	23 131
Average of annual workload	2.9	3.4	3.8	3.9	3.6	3.2

The changing trends in the workload for the various types of work during each period was related to the number of workers employed in the corresponding period. In the early days, there was only a small number of people working in diagnostic radiology, and at the end of the period, there was an increase in the number of retirees, so there was less work during these two periods. The workload for all types of work was the highest in 1980–1989, except for interventional radiology.

The average annual workload was defined as the ratio of the total workload to the total person-time of medical diagnostic X-ray workers within a given period. The average annual workload for each type of work in each period did not change much, except for radiography, fluoroscopy (excluding group), and gastrointestinal radiography. The average annual workload for radiography and gastrointestinal radiography increased with time, and the trend for fluoroscopy (excluding group) was the opposite.

The workload was further classified according to the characteristics of the various types of work in the diagnostic process. Radiography effectively has a short exposure time—in particular, no bedside operation is needed. Depending on the operating conditions, the workloads of fluoroscopy (excluding group) and group fluoroscopy were divided into 'working in compartments' and 'working near X-ray source'. Under the same operating conditions, the workload was further divided into four categories on the basis of the protective equipment worn. The distribution of the workload for fluoroscopy was divided according to the operating conditions and protective measures, as shown in Table 2.

Gastrointestinal radiography, interventional radiology, and bone reduction under fluoroscopy requires workers to be near the X-ray source to position the patient's body, conduct an operation, support the bone, etc. They were divided up according to operating conditions and protective measures, as shown in Table 3.

Because medical diagnostic X-ray devices used in the same type of work have changed over time, differing in the ratings of their working conditions and in the degree of shielding for the worker, the type of medical diagnostic X-ray device is considered to be an important factor in dose estimation. In this study, the type of medical diagnostic X-ray device was not further classified, so much work can be done to improve the dose estimation process in the future.

Dose results

After collecting the above information, the annual occupational exposure dose for 3702 medical diagnostic X-Ray workers from 1950 to 2011 in Jiangsu, China was calculated using the established dose calculation software. The dose was given in the form of a matrix with 3702 rows and 62 columns. The dose results for the years in which workers did not engage in medical X-ray diagnostic work were set as zero.

In order to confirm the applicability of the results, a quantity with statistical significance, the average annual dose, was introduced. The changes in average annual doses over various periods are shown in Table 4. The average annual dose for medical workers in our study peaked during the early 1950s and then declined, reaching very low levels by the mid-1990s and remaining at those levels thereafter. The annual average dose for the period of 1996–2011 for these workers was 1.1 mSv, which is numerically over two-fold lower than the annual background radiation dose of 2.4 mSv.

Table 2. Distribution of the workload for fluoroscopy (excluding group) and group fluoroscopy as divided by operating conditions and protective measures (thousand person-time)

	<1960	1960–1969	1970–1979	1980–1989	1990–1999	2000—
Fluoroscopy (excluding group)						
in compartment conditions	843	2998	19 329	57 113	61 965	42 306
near X-ray source						
with lead chair and lead apron	1709	8948	21 338	16 839	5960	2438
with lead chair, without lead apron	5340	13 768	20 744	14 865	1424	101
with lead apron, without lead chair	1105	2991	9218	9880	6849	5521
without lead chair and lead apron	8911	10 870	14 331	12 901	7118	468
Group fluoroscopy						
in compartment conditions	697	2147	11 934	30 559	25 670	19 233
near X-ray source						
with lead chair and lead apron	584	3926	17 150	15 402	5266	2024
with lead chair, without lead apron	0	200	370	497	98	29
with lead apron, without lead chair	212	2563	10 648	9259	3144	1095
without lead chair and lead apron	37	541	1782	2043	1029	750

Table 3. Distribution of the workload for gastrointestinal radiography, interventional radiology, and bone reduction under fluoroscopy as divided by operating conditions and protective measures (thousand person-time)

	<1960	1960–1969	1970–1979	1980–1989	1990–1999	2000—
Gastrointestinal radiography						
with lead apron	688	3168	9593	13 863	11 038	6335
without lead apron	1259	2361	4270	6715	6741	4908
Interventional radiology						
with lead apron	0	0	0	53	87	101
without lead apron	0	0	0	24	60	61
Bone reduction under fluoroscopy						
with lead apron	42	154	544	742	550	251
without lead apron	2	13	43	115	150	145

Table 4. Average annual dose in different periods ($mSv \cdot a^{-1}$)

Period (years)	Range of 95% confidence level				Number of person-years
	Av.	Up	Down	Max.	
50–54	12.38	13.06	11.70	218	1528
55–59	10.76	11.31	10.21	218	2477
60–64	7.72	8.09	7.35	218	3929
65–69	5.36	5.67	5.05	258	5169
70–74	3.88	4.09	3.67	258	8584
75–79	2.91	3.07	2.75	235	14 806
80–84	2.32	2.45	2.19	218	17 035
85–89	1.71	1.81	1.61	218	15 533
90–94	1.51	1.61	1.41	175	13 619
95–99	1.22	1.32	1.12	166	10 981
00–04	1.09	1.18	1.00	166	8051
05–11	1.04	1.13	1.95	88	7576

Assessment

In order to evaluate the dose results, 21 medical diagnostic X-ray workers in different hospitals were monitored by thermoluminescent dosimeter (TLD) every 3 months for 21 months, and the indirect information used to estimate their doses was also collected. From the indirect information gathered, we found that for each worker, the type of work, workload, and protection conditions remained unchanged for 21 months. The assessment results are shown in Table 5. The estimation results are very close to the TLD monitoring results.

DISCUSSION

In the absence of personal dose-monitoring data, more comprehensive indirect information (workload, operation status and protective measures, etc.) was collected using the questionnaire method. This provided the dose information for research on the dose effect. In order to ensure the reliability and authenticity of the survey data, some important quality assurance measures were applied during the investigation and data input process. After collecting the indirect information used to estimate the dose and workload, the types of protective conditions (important information required and collected for dose estimation using the retrospective dosimetry method) were classified. Using dose calculation software based on the retrospective dosimetry method, the annual dose for 3702 medical diagnostic workers was calculated.

From Equation 3, the uncertainty in the dose estimation was determined by the type and workload of each worker, and the conversion factor (C_{KT} and C_{KP}). First, due to the differences in distance from the radioactive source, proficiency with the operating radiation equipment, and protective properties, even medical diagnostic X-ray workers engaged in the same type of work were exposed to vastly different doses. Second, due to management confusion regarding workload for medical diagnostic X-ray workers in hospitals, or recall bias of respondents around workload, the uncertainty of the dose caused by workload uncertainty was difficult to assess and cannot be ignored. Finally, the conversion coefficients are given in terms of monoenergetic photon energy in the ICRP Report, but the radiation produced by a medical diagnostic X-ray device is a continuous X-ray spectrum characterized by the tube voltage. The tube voltage range of medical diagnostic X-ray devices is 60 kV to 100 kV (and the range of effective energy is 28.8 keV to 34.5 keV); C_{KP}/C_{KT} is 1.669 to 1.785. The uncertainty caused by the conversion factor is approximately –3.9% to 2.7%, which is negligible compared with the other two factors.

Between 1990 and 2000, the average annual dose of the cohort was numerically in good agreement with the average annual effective dose from diagnostic radiology in China [8], which is shown in

Table 5. TLD monitoring results and estimation results of 21 medical diagnostic X-ray workers in different hospitals (mSv)

No.	TLD results confidence level of 95%			Estimation results	No.	TLD results confidence level of 95%			Estimation results
	Average	Down	Up			Average	Down	Up	
1	0.13	0.10	0.16	0.04	12	0.02	0.02	0.02	0.00
2	0.05	0.02	0.07	0.02	13	0.02	0.02	0.02	0.92
3	0.04	0.01	0.07	0.13	14	0.03	0.01	0.05	0.01
4	0.03	0.01	0.05	0.07	15	0.11	0.05	0.17	0.10
5	0.04	0.01	0.06	0.55	16	0.09	0.00	0.20	0.22
6	0.03	0.01	0.06	0.63	17	0.10	0.04	0.15	0.13
7	0.04	0.02	0.07	0.02	18	0.03	0.01	0.04	0.00
8	0.02	0.02	0.02	0.02	19	0.05	0.01	0.09	0.13
9	0.04	0.02	0.07	0.17	20	0.02	0.02	0.02	0.39
10	0.02	0.02	0.02	0.02	21	0.03	0.01	0.04	0.01
11	0.05	0.01	0.10	0.05					

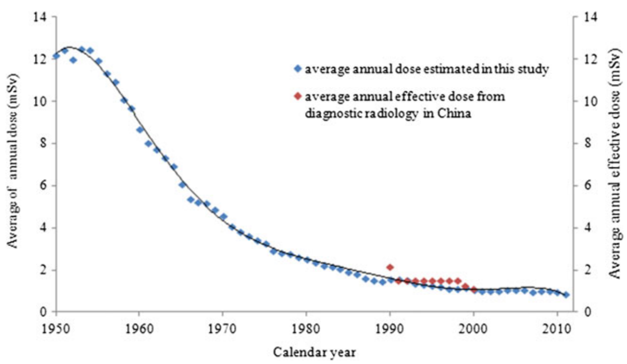

Fig. 3. Average annual dose for medical diagnostic X-ray workers in Jiangsu, China (N = 3702), 1950–2011.

Fig. 3. In other studies, the changes in mean annual dose over time from 1951 to 1987 in Canada [9] displayed the same trend as in our study.

Moreover, the idea of the establishment of a retrospective dosimetry method was derived from the definition of the effective dose, which was proposed in Publication 60 (ICRP). The effective dose can provide a value, which does not take into account the characteristics of a specific individual, but only considers the given exposure conditions. The effective dose is based on the mean doses in organs or tissues of the human body. Similarly, the establishment of a retrospective dosimetry method, which takes into account the state of exposure, but not the characteristics of a specific operation, is based on the average dose due to occupational exposure in workers.

The estimated model is based on a hypothetical infinite number of radiation workers using different diagnostic equipment under different protective conditions. The dose from occupational exposure in radiological diagnosis staff is related to the quality of the protection and the characteristics of specific types of radiation work. The calculated amount of radiation workers receive in the process of diagnosis (using the retrospective dose radiation method) is a statistic, only representing the expected values as calculated by this model, not accurate dose values.

CONCLUSIONS

The dose as calculated by the retrospective dosimetry method can truly indicate the degree of a worker's exposure in medical X-ray diagnostic work.

Recommendations

The retrospective dosimetry method is universal, but the correction coefficient of dose r_k is unique. This is the result of analysis of a large sample survey, which is related to the specific national or local standards for radiological health and departmental regulations.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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REFERENCES

1. UNSCEAR. United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. *2000 Report to the General Assembly, with scientific annexes,* United Nations, New York, 2000.
2. Yi Y, Zheng J, Zhuo W et al. Trends in radiation exposure from clinical nuclear medicine procedures in Shanghai, China. *Nucl Med Commun* 2012;33:331–6.
3. Wang F, Sun Q, Wang J et al. Risk of developing cancers due to low-dose radiation exposure among medical X-ray workers in China—results of a prospective study. *Int J Clin Exp Pathol* 2016;9:11897–903.
4. Zhang LA, Zhang WY, Chang HX et al. Statistical analysis of individual doses received by medical diagnostic X-ray workers. *Chin J Radiol Med Prot* 1992;12:6.
5. Zhang L, Jia D, Chang H et al. A retrospective dosimetry method for occupational dose for Chinese medical diagnostic X-ray workers. *Radiat Prot Dosimetry* 1998;77:69–72.
6. International Commission on Radiological Protection. Conversion coefficients for use in radiological protection against external radiation. ICRP Publication 74. *Ann ICRP* 1996;**26** (3–4).
7. Kato H, Hayashi N, Suzuki S et al. Problems of the effective energy used as a quality expression of diagnostic X-ray. *Nihon Hoshasen Gijutsu Gakkai Zasshi* 2011;67:1320–6.
8. Tian Y, Zhang L, Ju Y. Dose level of occupational exposure in China. *Radiat Prot Dosimetry* 2008;128:491–5.
9. Zielinski JM, Garner MJ, Band PR et al. Health outcomes of low-dose ionizing radiation exposure among medical workers: a cohort study of the Canadian national dose registry of radiation workers. *Int J Occup Med Environ Health* 2009;22: 149–156.