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ORIGINAL RESEARCH

On-Site Evaluation and Improvement Strategies of Radiation Occupational Hazard Prevention and Control Effectiveness in Medical Institution Construction Projects

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Objective: To evaluate the control effectiveness of medical institution construction projects, and to summarize and analyze the radiation protection management status and improvement strategies of relevant medical institutions.

Methods: A total of 40 medical institutions in our city were evaluated for control effectiveness through measures such as data research, on-site investigations, equipment quality testing, and radiation health protection inspections.

Results: The compliance rates of personnel configuration, verification of protective measures, and radiation protection management and emergency response were 95.0%, 67.5%, and 70.0%, respectively. Compared to earlier evaluation periods (eg, before the implementation of new DR performance testing standards, where compliance rates were below 60%), there has been a marked improvement in compliance with performance and protection testing, particularly after the introduction of updated evaluation criteria. The first-pass rates of performance testing for DSA, DR, CT, and dental equipment were 100%, 84.0%, 92.0%, and 100%, respectively. The first-pass rates of radiation protection inspection for related equipment rooms were 100%, 100%, 92.0%, and 100%, respectively. New DR performance testing standards introduced specialized testing items, such as dark noise, detector dose indication (DDI), and signal transmission characteristics (STP), which presented initial challenges due to the unavailability of pre-processing images in some manufacturers' products. Additionally, higher monitoring values were identified at doors, door gaps, and cable penetration points in equipment rooms. Regarding radiation protection management and emergency response, issues such as overly rigid emergency response plans, insufficient personal dose management, and inadequate occupational health examinations remain, requiring systematic adjustments.

Conclusion: At present, the awareness of radiation hazard prevention and control in medical institutions has been improved. Compared to earlier periods of testing and evaluation, there has been a significant improvement in the degree of compliance with performance and protection testing. Medical institutions have strengthened equipment annual inspections, quality control, and other management work, further enhancing the level of radiation protection management.

Keywords: radiation health management, medical institution, construction project, radiation occupational hazard, prevention and control effectiveness, on-site evaluation, improvement strategies

In recent years, with the rapid development of medical technology and the increasing popularity of medical services, radiological diagnosis and treatment have become indispensable tools in the medical field.[1] From conventional X-ray imaging to more advanced techniques such as computed tomography (CT), digital radiography (DR), and digital subtraction angiography (DSA), radiological technology has been widely applied in clinical diagnosis, surgical navigation, and treatment, bringing revolutionary changes to medical diagnostics and treatment[2]. However, accompanying the widespread use of radiological technology is the potential occupational hazards of radiation exposure.[3] Prolonged exposure to radiation among healthcare workers increases the risk of occupational diseases such as leukemia and thyroid

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cancer, while patients undergoing radiological diagnosis and treatment also face potential risks of radiation-induced injury.[4,5] Therefore, effective prevention and control of radiation hazards in medical institutions are not only crucial for the health and safety of healthcare workers but also directly impact the quality of life and medical safety of patients. Especially in medical institution construction projects, the introduction and use of radiological equipment will become a core aspect of medical services. Throughout the procurement, installation, commissioning, and operation of equipment, strict adherence to relevant radiation protection management regulations and standards is necessary to ensure the safe operation of medical facilities and the occupational health of healthcare workers.

However, the reality often falls short of the ideal situation. In our city, despite the government and relevant departments issuing a series of regulations and standards for radiation protection management in medical institutions, there are still some problems and challenges in the actual implementation process. For example, medical institutions may have inadequate radiation protection equipment, insufficient personnel training, and lax radiation protection measures, all of which may affect the effectiveness and practicality of radiation health and safety management.[6] Therefore, to comprehensively understand the current status of radiation protection management in medical institutions in our city, evaluate its control effectiveness, and propose corresponding improvement strategies for existing problems, this study conducted a control effectiveness evaluation of 40 medical institutions. Through data research, on-site investigations, equipment quality testing, and radiation health protection inspections, we aim to provide objective data support and scientific recommendations to enhance the radiation protection management level of medical institutions in our city, ensuring the safety of healthcare workers and patients and promoting the sustainable development of medical services.

Materials and Methods

Ethics Approval and Consent to Participate

This study was approved by the ethics committee of Heilongjiang Provincial Second Hospital. Informed consent was obtained from all study participants. All the methods were carried out in accordance with the Declaration of Helsinki.

Study Subjects and Detection Instruments

Control effectiveness evaluation was conducted on 40 medical institutions, including 27 public hospitals and 13 private hospitals. A total of 85 X-ray imaging devices were involved in the evaluation, including DSA, CT, DR, and dental equipment, as shown in Table 1.

Evaluation Method

Through comprehensive data research and on-site inspections, the personnel allocation, verification of protective measures, and compliance with radiation protection management (see Table 2) and relevant laws, regulations, and standards were thoroughly analyzed. Meanwhile, for the radiation facilities and equipment quality of medical institutions, objective evaluation methods such as equipment quality testing and radiation health protection testing were adopted for comprehensive assessment. The testing items and standards are detailed in Table 3, and the conformity judgment and statistical analysis of the testing results were conducted. In the CT rooms, measurements of radiation protection leakage were conducted to assess dose rates and annual effective doses. Dose rates (μSv/h) were measured at various key points, including door gaps, cable ducts, and wall penetrations, using a high-precision ion chamber dosimeter. The annual effective dose (mSv) was calculated based on the measured dose rates and standard occupancy factors as specified in GBZ 130–2013.

Table 1 Overview of Medical Institutions

Institution Type	n	Installed Equipment			
		CT	DR	DSA	Dental Equipment
Public Hospitals	27	17	34	3	5
Private Hospitals	13	8	16	1	1

Table 2 Evaluation Content and Basis

Evaluation Item	Evaluation Content	Evaluation Basis
Personnel Allocation	Personnel allocation of project units	Occupational Disease Prevention and Control Law of the People's Republic of China; Regulations on the Administration of Medical Treatment by Radiation; Regulations on the Safety and Protection of Radioisotopes and Radiation Devices; Measures for the Occupational Health Management of Radiological Workers; GBZ 130–2013; GBZ 128–2016
Verification of Protective Measures	Room size, layout, shielding measures, monitoring zones, interlocking devices and warning signs, personal protective equipment, ventilation measures	
Radiation Protection Management	Radiation accident emergency response, management organization, personal dose management, occupational health examinations, education and training, record management	

Table 3 Testing Items and Standards

Testing Type	Inspected Equipment	Testing Items	Standard
Performance	DR	Deviation of tube voltage indication; Reproducibility of output; Half-value layer of useful beam; Deviation of exposure time indication; Deviation of verticality of useful beam; Deviation of four edges of light field and irradiation field; Dark noise; Detector dose indication; Signal transmission characteristics; Response uniformity; Measuring distance error; Residual image; Ghosting; Limit spatial resolution; Low contrast details; AEC sensitivity; Consistency between AEC ionization chambers; Consistency of AEC tube voltage variation	WS 76–2017, WS 521–2017
	CT	Diagnostic bed positioning accuracy; Positioning light accuracy; Reconstruction layer thickness deviation; CTDIw; CT value; Uniformity; Noise; High contrast resolution; Low contrast detectability; Linearity of CT values	GB 17589–2011
	DSA	Air kerma free in air; Dynamic range; DSA contrast sensitivity; DSA visual spatial resolution; Ghosting; X-ray tube voltage; Total filtration; Radiation output repeatability, linearity; Half-value layer	GB/T 19042.3–2005
	Dental Equipment	Deviation of tube voltage indication; Reproducibility of radiation output; Half-value layer of useful beam; Total filtration; Image uniformity; Patient positioning indicator; Panoramic layer	GB/T 19042.4–2005
Protection	CT Rooms	Ambient dose equivalent rate outside the room (μSv/h); Annual effective dose (mSv)	GBZ 130–2013

Results

Compliance of Some Evaluation Results of Construction Project Units With Relevant Laws and Regulations

The compliance statistics of personnel allocation, protective measures, and radiation protection management and emergency response situations of 40 medical institutions with relevant laws and regulations are shown in Table 4 below.

Table 4 Compliance of Some Evaluation Results of Construction Project Units With Relevant Laws and Regulations

Verification	Personnel Allocation		Verification of Protective Measures		Radiation Protection Management and Emergency Response	
	n	%	n	%	n	%
Compliance	38	95.0%	27	67.5%	28	70.0%
Basic Compliance	0	0.0%	10	25.0%	10	25.0%
Non-compliance	2	5.0%	3	7.5%	2	5.0%

Notes: Compliance refers to full adherence to the standards, while Basic compliance indicates minimal acceptable adherence.

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Personnel Allocation

Among the 40 medical institutions, two failed to meet the requirements for allocating radiology personnel stipulated in the Regulations on the Administration of Medical Treatment by Radiation.[7] Both of these institutions are private hospitals. One of them, equipped with DR equipment, uses assistant physicians as radiologists; while the other, equipped with CT equipment, designates internal medicine physicians as radiologists. Neither of these cases fulfills the requirement of having specialized radiologists as per the regulations.

Verification of Protective Measures

Among the 40 medical institutions, 10 were unable to fully comply with the relevant regulations or standards, with 3 institutions showing obvious non-compliance with the relevant standards (see Table 5). These non-compliance cases primarily focused on the size of the room, with all 3 involved institutions having DR equipment rooms. The effective areas of these rooms were 18.6 m², 17.5 m², and 17.9 m² respectively, all below the standard requirement (20.0 m²).

Radiation Protection Management and Emergency Response

Among the 40 medical institutions, 12 were unable to fully meet the requirements of radiation protection management and emergency response, indicating some deficiencies in management (see Table 6). Deficiencies in radiation accident emergency response primarily stem from unclear procedures and some degree of procedural confusion. In terms of management organization, there are cases where radiation workers double as management personnel, which could affect the professionalism and efficiency of management. Issues with personal dose management mainly include the loss of personal dosimeters and exceeding monitoring periods, which could impact the personal radiation safety of healthcare workers. Problems in occupational health management and record management mainly involve missing items in physical examinations and the failure to establish timely occupational health monitoring records for radiation workers, potentially affecting the occupational health and safety of healthcare workers.

Table 5 Summary of Protective Measures Verification

Verification	Compliance	Partial Compliance	Non-Compliance
Room Size Area	38	0	3
Room Layout	38	2	0
Shielding Measures	40	0	0
Monitoring Zones	40	0	0
Interlock Devices & Warning Signs	36	4	0
Personal Protective Equipment	37	3	0
Ventilation Measures	39	1	0

Table 6 Summary of Radiation Protection Management and Emergency Response Verification

Verification	Compliance	Partial Compliance	Non-Compliance
Radiation Accident Emergency Response	37	3	0
Management Organization	39	1	0
Personal Dose Management	37	3	0
Occupational Health Check	38	2	0
Education and Training	40	0	0
Record Management	37	1	2

Table 7 Results of Performance Testing and Room Shielding Protection Testing

Equipment Type	n	Test Occurrence	Performance Testing		Shielding Testing	
			n	%	n	%
CT	25	Initial	23	92.0%	23	92.0%
		Reinspection	25	100.0%	25	100.0%
DR	50	Initial	42	84.0%	50	100.0%
		Reinspection	50	100.0%	50	100.0%
DSA	4	Initial	4	100.0%	4	100.0%
		Reinspection	4	100.0%	4	100.0%
Dental	6	Initial	6	100.0%	6	100.0%
		Reinspection	6	100.0%	6	100.0%

Table 8 Summary of Non-Compliance During Initial Inspection

Equipment Type	CT	DR
Non-compliant Parameters and Quantity	CT value linearity (2 times)	Dark noise (2 times); Detector dose indication (2 times); Signal transmission characteristics (1 time); Spatial resolution (3 times)
Leakage Positions Identified During Shielding Testing	Cable duct (1 time); Control room shielding door (1 time)	N/A

Equipment Performance Testing and Radiation Monitoring

The compliance rates of initial and subsequent inspections for performance and room shielding protection of the 85 devices across 40 medical institutions are presented in Table 7. Details of non-compliance during the initial inspection are outlined in Table 8. In terms of performance testing, the initial inspection results for DSA and dental equipment met the relevant standard requirements. However, the initial compliance rates for DR and CT equipment were 84.0% and 92.0% respectively. Following reinspection, both compliance rates reached 100%. During the reinspection of DR equipment, non-compliance during the initial inspection was primarily related to dark noise, detector dose indication, signal transmission characteristics, and spatial resolution. For CT equipment, non-compliance parameters mainly involved CT value linearity. Regarding room radiation protection testing, the initial compliance rate for CT equipment rooms was 92.0%, with instances of exceeding monitoring points, mainly concentrated at the room's door structure, cable duct wall penetrations. After rectification, the reinspection compliance rate reached 100%.

Discussion

Personnel Configuration

Among the 40 medical institutions, two failed to allocate imaging physicians with the professional category of "Medical Imaging and Radiation Therapy." In China, township health centers and remote areas often struggle to meet the personnel configuration requirements. In response to this situation, considering that national policies allow for multi-site practice, project units should fully utilize this policy by promptly assigning qualified imaging physicians to participate in construction projects through multi-site practice. Regarding personnel configuration, medical institutions should, based on compliance with the regulations of radiation diagnosis and treatment management, reasonably allocate relevant radiation workers according to the actual operational needs of the project. For example, when performing interventional radiology diagnosis and treatment, in addition to imaging physicians and technicians, consideration should also be given to including relevant internal and external physicians, as well as nurses involved in surgical processes, within the management scope of radiation workers. To address high-intensity work demands, medical institutions should appropriately increase the number of radiation workers and adjust work hours reasonably to ensure that radiation workers meet the target management values for radiation dose. Additionally, medical institutions should promptly handle qualification certificate changes for relevant personnel in cases of new recruitments or unit

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name changes. For example, timely processing of changes in the practice location for medical practitioner certificates and changes in the work unit for radiation worker certificates to ensure the effectiveness and compliance of personnel qualifications.

Protection Measures Verification

Room Size

Due to various factors, including site limitations and initial planning deficiencies, some medical institutions face situations where they cannot meet the requirements of relevant standards for room size.[8] A typical case is the direct use of old rooms for renovation. Although the old rooms met national standards at that time, during the process of removing old equipment and installing new equipment, the room size may fail to meet the current valid national standards. Especially during the renovation process, it may be impossible to achieve the required room size due to the inability to move certain shielding structures, resulting in the room size not meeting the requirements. To address this issue, medical institutions should consider reasonable room layout and design to ensure a certain degree of surplus relative to the standard requirements when planning related rooms. Additionally, appropriately increasing the room size can not only better meet the installation conditions of equipment but also reduce the shielding requirements for radiation-sensitive environments such as room doors and windows.[9] Doing so can ensure that the likelihood of exposure is kept at a reasonably low level, thereby ensuring the safety of medical staff and patients.

Room Layout

Some medical institutions fail to adequately consider equipment installation positions during equipment installation. For example, some medical institutions fail to consider directing the beam away from room doors and windows, which are radiation shielding weak points, when installing DR equipment.[10] Additionally, when installing CT equipment, if the framework is too close to the wall, it can prevent effective convection of room doors and ventilation openings.[11] Furthermore, the external layout of the room also needs to be considered, such as setting up dual channels for medical staff and patients to enter and exit the room conveniently and facilitating the management of medical staff towards patients and outsiders. To address this issue, medical institutions should communicate fully with equipment manufacturers and evaluation agencies, comprehensively consider factors such as equipment placement, clinical use, personnel management, and shielding effectiveness, and reasonably set up the layout inside and outside the room. Doing so can not only ensure the safe operation of equipment and patient safety but also improve the efficiency and quality of medical services.

Interlocking Devices and Warning Signs, Personal Protective Equipment, and Ventilation Measures

During on-site verification, it was found that some medical institutions had inadequate understanding of relevant regulations and standards. For example, some project units had warning signs with incorrect warning statements, colors that did not meet standard requirements, and were not posted at all entrances and exits.[12] Additionally, there were issues with the configuration of personal protective equipment, such as shortages, sharing, and improper lead equivalence,[13] and they were not worn by patients during clinical examinations as required. The ventilation effect in patient examination room was also poor, with adjacent exhaust and supply air vents unable to create a good airflow. Moreover, powered exhaust ventilation devices were not connected to external ventilation ducts, resulting in ineffective ventilation.[14] To address these issues, it is recommended that medical institutions procure warning signs that comply with national standard requirements and prominently display them at all entrances and exits. Project units should provide radiation workers, patients, and examinees with personal protective equipment that meets lead equivalence requirements based on relevant standard requirements and clinical practice needs. For example, when using DR equipment for physical examinations, consider providing mobile lead protective screens to improve wearing efficiency. For CT equipment, it is suggested to purchase sufficiently sized lead aprons to ensure effective protection for individuals of all body types. Additionally, ventilation vents should be positioned in areas where effective ventilation is possible, especially ensuring good ventilation near radiation devices. The penetration position of ventilation devices through walls should avoid being close to useful beam areas to ensure the safety of medical staff and patients.

Shielding Measures

During the design and construction of shielding rooms, medical institutions lacked sufficient supervision, had inadequate understanding of shielding requirements, and failed to follow the principle of optimal protection. Some medical institutions had overly conservative or excessively conservative shielding, resulting in shielding lead equivalences far exceeding national standards, increasing the economic burden on medical institutions, and potentially affecting shielding effectiveness and the environment, leading to unnecessary resource waste.[15] Additionally, due to insufficient room size and improper equipment installation position selection, some medical institutions had weak shielding. For example, a hospital installed CT equipment too close to the side shielding, resulting in shielding design values meeting national standards but protection monitoring values outside the shielding being excessively high or even exceeding the standard.[16] Furthermore, the quality of shielding construction significantly affects shielding effectiveness. For instance, issues such as incomplete cement filling between brick layers, cracks in protective coatings, improper installation of observation windows, and inadequate overlap between motor room doors and walls directly affect shielding effectiveness.[17] To address these issues, medical institutions should enhance quality control during equipment installation and shielding construction. This includes ensuring proper alignment of shielding materials, complete cement filling between layers, and strict supervision during the construction process. Additionally, clear communication with evaluation agencies about any design modifications during construction is crucial to maintain compliance with safety standards. These measures can ensure effective shielding, minimizing radiation exposure for both staff and patients.

Radiation Protection Management and Emergency Response

Establishing corresponding radiation protection management systems is crucial for more effectively preventing and controlling occupational hazards from radiation.[18] The regulations and systems established by medical institutions should cover the establishment of radiation protection organizational structure and clarification of its responsibilities, radiation protection management systems, equipment operation procedures, work processes, quality control measures, personal dose monitoring, occupational health surveillance, and radiation protection training, among other aspects. Additionally, emergency organizational structures should be established with clear responsibilities, and radiation accident emergency response plans should be formulated to promptly and effectively address potential radiation accidents. However, the radiation accident emergency response plans and radiation regulations and systems of medical institutions are often overly dogmatic and less applicable to actual situations. Furthermore, due to the failure of medical institutions to effectively verify the qualifications of institutions conducting occupational health examinations, they have not been able to correctly select the examination categories for radiation workers. In terms of personal dose management, medical institutions often lack sufficient emphasis, leading to situations such as the loss of dosimeters or failure to replace them in a timely manner according to the prescribed period.[19] Therefore, medical institutions need to make appropriate adjustments to regulations and emergency response plans to ensure that they can better adapt to actual work needs. Meanwhile, supervision of institutions conducting occupational health examinations should be strengthened to ensure the selection of appropriate examination items and institutions. In terms of personal dose management, medical institutions should increase their emphasis on management to ensure the effective use and regular replacement of dosimeters, thereby safeguarding the health and safety of radiation workers.

Radiation Monitoring Results

Equipment Performance Testing

During the actual testing of 40 medical institutions, we identified some issues for discussion: ① In the determination criteria for the parameter of spatial resolution, it is required to achieve ≥90% of the baseline value. However, due to the large gap between adjacent line pairs in commonly used high-contrast resolution test cards, in some tests, it is not possible to cover the area ≥90% of the baseline value, resulting in the inability to strictly determine according to the standard. ② Currently, most DR equipment cannot obtain or directly obtain pre-processed images, resulting in the inability to complete the standard-required parameter tests for dark noise, DDI, STP, and response uniformity, leading to deficiencies in the test results. ③ In low-contrast detail detection, the criterion is that the number of detail changes

compared to the baseline value should not exceed 2. However, this cannot be implemented in actual testing, and the low-contrast detection phantoms recommended in the standard have differences in their own contrast and strong distribution specificity, which can cause inconvenience in the execution of the determination criteria during actual testing. ④ Deviation of CT value linearity is mainly influenced by reconstruction algorithms and some equipment calibration techniques, but it is currently impossible to intervene in this. ⑤ Some equipment has high requirements for factory index requirements in technical parameters, which cannot meet the standard requirements in the actual acceptance process, and it is necessary to compare testing methods and bases with the manufacturer to ensure that non-compliance is not blindly determined. Since the introduction of the new DR standard has been relatively short, a deeper understanding and practice of many parameters require radiation health technology service organizations to seek cooperation from manufacturers to comprehensively and systematically test the performance of DR. Moreover, the interactions with equipment manufacturers highlighted in this study provide critical insights for users and acceptance test personnel. By addressing challenges such as inaccessible pre-processed images for testing and aligning testing methods with manufacturer-provided indices, these collaborations ensure a more comprehensive and standardized evaluation process. Such partnerships not only help in identifying areas for improvement in equipment design and operation but also contribute to enhancing the reliability and safety of radiation protection measures. This approach underscores the importance of proactive communication and joint efforts between evaluation agencies, medical institutions, and manufacturers in ensuring the effectiveness of radiation monitoring and performance testing.

Radiation Protection Testing

Regarding the occurrence of protection leaks in CT rooms (part 3.2.4), the main reasons for the problem need to be analyzed. In actual monitoring, it was found that the main reasons for the radiation protection leakage in CT room include improper equipment installation, substandard shielding material quality, and construction process defects.[20] These factors may cause holes or defects in the shielding body, leading to radiation leaks exceeding the limits required by the standards. Therefore, medical institutions need to strengthen quality control during equipment installation and room construction, ensure the effectiveness and integrity of the shielding body, promptly detect and repair leakage problems, and ensure the safety of medical staff and patients. For DR rooms, the standard requires that the annual effective dose constraint value for personnel outside the room should not exceed 0.25 mSv. Although the vast majority of medical institutions meet the standard requirements under the premise of reasonable workload control, during actual protection monitoring, some medical institutions found that the ambient dose equivalent rate outside the DR room was relatively high. The direction of the cable beam used by DR equipment is primary radiation, which has high penetrability, so the corresponding shielding requirements are higher.[21] During the detection and evaluation process, attention should be focused on this situation, and medical institutions are advised to strengthen the shielding measures and management of corresponding locations to ensure that the safety of surrounding personnel remains at a reasonably low level of radiation exposure.

Conclusion

The evaluation of radiation occupational hazard control effectiveness in construction project units is critical for preventing potential radiation hazards. This study demonstrates significant improvements in radiation protection awareness, management, and compliance, with performance and protection testing compliance rates improving from 84.0% and 92.0% during initial testing to 100.0% after reinspection. However, gaps remain in areas such as personal dose monitoring (75% compliance) and occupational health surveillance (95% compliance), highlighting the need for further enhancements. To address these issues, medical institutions should allocate personnel based on operational needs, optimize room layouts and shielding construction, and strengthen radiation protection management through improved training and emergency response plans. These findings underscore the potential for broader application of this evaluation approach in regions with similar safety regulations, fostering improved radiation hazard prevention and management.

Disclosure

The authors report no conflicts of interest in this work.

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