

# Study on Design Quality Evaluation Model of Radiation Protection Engineering in General Hospitals Based on Life Cycle Concept

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**Abstract:** With the continuous expansion of radiological diagnostic equipment in Chinese general hospitals, the design quality of radiation protection engineering directly affects the radiation safety of medical staff, patients and the surrounding public. This study introduces the concept of the entire life cycle into the field of assessment of the design quality of radiation protection engineering. By identifying the quality influencing factors in each stage including planning and design, construction implementation, operation and maintenance iteration, as well as decommissioning disposal, an assessment index system was constructed, the model application scenarios in different stages were clarified, and a guarantee mechanism was proposed from three dimensions: organizational system, technical data, and personnel capability. The research results can provide some reference for the whole life cycle management of the design quality of radiation protection engineering in general hospitals, so as to reduce the radiation safety risk and improve the long-term effectiveness of radiation protection engineering.

**Keywords:** General hospital; Radiation protection engineering; Design quality assessment; Entire life cycle; Evaluation model

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## 1. Introduction

Radiation protection engineering in a general hospital is a systematic engineering, covering the design of shielding structures in radiation diagnosis and treatment areas, the configuration of protective facilities, and the deployment of radiation monitoring systems. Its design involves numerous elements, and scholars at home and abroad have conducted extensive research on the quality assessment system for such designs<sup>[1]</sup>. However, most studies only focus on the design stage. Based on this, this paper comprehensively analyzes the design quality assessment in the whole life cycle of hospital radiation protection project, forms an index system, and provides some reference for improving the design quality.

## **2. Factor identification and evaluation index system construction**

### **2.1. The entire life cycle of the radiation protection project**

The entire life cycle of the radiation protection project can be divided into four stages. The first stage is the planning and design stage, which includes the layout planning of the radiology department, the calculation of shielding parameters, the selection of protective materials, and the design of radiation monitoring points. This is the source stage that determines the overall quality of the protection project; the second stage is the construction and implementation stage, involving the construction of shielding structures, the installation of protective doors, and the sealing treatment of pipe intersections, which is the implementation stage of converting the design intention into a practical project; the third stage is the operation and iterative stage, including daily radiation monitoring, the maintenance of protective facilities, and the adjustment of protective measures during equipment updates and renovations, which is an important stage for ensuring that the project continuously meets the protection requirements over the long term; the fourth stage is the decommissioning and disposal stage, including the decommissioning of radiation equipment, the removal of protective facilities, and the detection and cleaning of radioactive contamination on the site, which is the closing stage for preventing radiation risks during the decommissioning phase. Based on the concept of project life cycle management, the impact of the quality of radiation protection project design has obvious lag. As the equipment ages and the structure is damaged, the parameter deviation from the design and construction phase will gradually become apparent, leading to the risk of radiation leakage <sup>[2]</sup>. Once a radiation leak occurs, it will not only affect the personnel within the hospital but also have an impact on surrounding buildings and the public. Therefore, the design quality assessment of the radiation protection project requires strict compliance review. The design must comply with the mandatory requirements of relevant national regulations, such as the Health Review Regulations for Diagnostic Radiology Projects and the Radiation Protection Requirements for Medical X-ray Diagnosis. It must match the equipment configuration planning, diagnostic process and spatial layout characteristics of the hospital radiology department, and also take into account the equipment renewal needs in the next 5 to 10 years. The feasibility of construction, the convenience of operation and maintenance, and the environmental friendliness of decommissioning disposal are fully considered to reduce the overall cost and safety risk during the whole life cycle <sup>[3]</sup>.

### **2.2. Identification and screening of factors affecting design quality**

To identify the factors that affect design quality, it is necessary to consider various factors comprehensively. This article mainly screens relevant materials through literature research. From 2018 to 2025, authoritative journal articles and industry reports on radiation protection engineering design and radiation safety assessment from both domestic and international sources were collected, and national and industry standards such as “Radiation Protection Regulations” and “Construction Specifications for Hospital Radiology Departments” were sorted out. The factors affecting quality and various indicators corresponding to mandatory provisions were extracted <sup>[4]</sup>. Comparisons were made with the practices of various hospitals, and common design quality influencing factors in practice were supplemented. Through deduplication and integration, a pool of 53 indicators affecting factors was initially formed. Among them, the planning and design stage includes 21 indicators such as the rationality of shielding parameter calculations and the adaptability of protective material selection; the construction implementation stage contains 13 indicators, such as the feasibility of design implementation and the completeness of protective design at

pipe intersection points; the iterative operation and maintenance stage contains 12 indicators, such as the rationality of radiation monitoring point design and the reserved space for protective facility maintenance; the decommissioning disposal stage contains 7 indicators, such as the convenience of protective facility removal and the completeness of pollution prevention design<sup>[5]</sup>. See **Table 1**.

**Table 1.** Expert categories and experience background

No.	Expert category	Number	Years of experience	Professional background
1	Radiation protection evaluation experts	7	≥ 10 years	1. 3 senior experts in radiation health monitoring/evaluation from provincial/municipal CDC 2. 2 technical directors of third-party radiation protection testing institutions 3. 2 senior engineers specializing in radiation protection evaluation in environmental impact assessment institutions
2	Hospital radiology department administrator	5	≥ 10 years	1. 3 directors/deputy directors of radiology departments in tertiary first-class hospitals (in charge of radiation protection) 2. 2 responsible persons for radiation protection management in nuclear medicine departments of tertiary general hospitals
3	Medical building designers from Class-A design institutes	4	≥ 10 years	1. 2 senior engineers specializing in radiation protection design from medical building specialized design institutes 2. 2 chief designers from medical building departments of comprehensive Class-A design institutes
4	Hospital infrastructure management personnel	4	≥ 10 years	1. 2 project leaders from infrastructure departments of tertiary first-class hospitals (have presided over radiology department reconstruction and expansion projects) 2. 2 specialists in charge of radiation protection projects in public hospital infrastructure management departments
Total	–	20	–	All experts have full-process experience in radiation protection engineering, covering the entire professional chain of design, evaluation, management and implementation

As shown in **Table 1**, in order to ensure the scientificity and practicability of the indicators, this study used the Delphi method to screen the 53 indicators initially extracted. 20 experts with over 10 years of working experience were invited to evaluate the importance of the indicators. The evaluation used a Likert 5-point scale, where 1 indicated completely unimportant and 5 indicated very important<sup>[6]</sup>. After two rounds of expert consultation, a total of 26 indicators are eliminated, the average importance scores below 3.5, the variation coefficient is greater than 0.25. These indicators, such as the qualification level of the construction unit and the professional level of operation and maintenance personnel, belong to the control content of the subsequent stage, as well as the popularity of the design unit and the working life of the designer. These indicators cannot directly reflect the quality of the design scheme itself, and are ultimately retained. Eventually, they were retained. A total of 27 core evaluation indicators were ultimately retained. The specific contents of these indicators are as follows. See **Table 2**.

**Table 2.** Evaluation index system for design quality of radiation protection engineering in general hospitals

Criterion layer	Index layer code	Index name	Index description
Planning and design adaptability (A)	A1	Scenario adaptability of shielding calculation parameters	The degree of fit between calculation parameters and actual scenarios such as hospital diagnosis and treatment processes, equipment usage frequency, etc., on the basis of meeting mandatory requirements
	A2	Design margin of main shielding layer thickness	The proportion of shielding layer thickness exceeding the minimum requirement, reflecting the redundant safety level and balancing safety and economy
	A3	Integrity of secondary shielding protection design	The full coverage degree of protection design for walls, floors, ceilings, etc. in non-main irradiation directions, without omitted areas
	A4	Sealing performance of protection design for pipeline crossing points	The rationality of sealing protection design at positions where water and electricity pipelines, exhaust ducts pass through the shielding layer
	A5	Adaptability of protection material selection	The adaptation degree of protection materials to application scenarios (e.g., whether high atomic number materials are selected for high-energy rays)
	A6	Rationality of radiology department layout and workflow	The clarity of the division of controlled areas and supervised areas, and the degree to which personnel streamline design avoids unnecessary radiation exposure
	A7	Reserved Space for future equipment upgrade	The redundant protection design reserved for equipment update in the next 5-10 years, reducing the difficulty of subsequent transformation
Construction feasibility (B)	B1	Technical feasibility of shielding structure construction	The degree to which the construction difficulty of the designed shielding structure is within the scope of existing technical capabilities
	B2	Market availability of protection materials	The degree to which the protection materials selected in the design belong to conventional purchasable categories in the market, avoiding supply risks of special materials
	B3	Rationality of fault tolerance design for construction errors	The degree to which the design considers the impact of construction errors and reserves reasonable parameter margin
	B4	Clarity of coordination design for cross construction	The clarity of protection requirements for construction intersection points between radiation protection engineering and HVAC, electrical and other specialties
	B5	Clarity of construction quality acceptance points	The detail degree of acceptance standards and testing methods for each key process specified in the design documents
	B6	Safety protection design for construction process	The perfection degree of temporary radiation protection measures during the construction stage considered in the design scheme
	B7	Controllability of construction cost	The degree to which the construction cost is controlled within a reasonable range under the premise of meeting protection requirements

Operation and maintenance sustainability (C)	C1	Rationality of radiation monitoring point design	The integrity degree of fixed radiation monitor positions covering all potential leakage points
	C2	Reserved maintenance space for protection facilities	The degree to which sufficient maintenance operation space is reserved around protection doors, interlock devices and other facilities
	C3	Redundant design of radiation interlock devices	The perfection degree of redundant backup design for safety devices such as door-machine interlock and working status warning
	C4	Interface design for operation and maintenance data collection	The perfection degree of reserved system interfaces for remote transmission of radiation monitoring data, automatic alarm, etc.
	C5	Compatibility design for local transformation	The rationality of design that does not require large-scale demolition of the original shielding structure when replacing local equipment
	C6	Life matching of protection facilities	The matching degree between the design life of protection facilities and the expected service cycle of radiation equipment
	C7	Supporting design of emergency response plan	The perfection degree of emergency disposal operation procedures and facility configuration in case of radiation accidents
Decommissioning environmental friendliness (D)	D1	Convenience design for dismantling of protection facilities	The degree to which shielding structures, protection doors and other facilities are convenient for safe dismantling, reducing pollution risk during dismantling
	D2	Radioactive pollution prevention and control design for decommissioning	The perfection degree of pollution detection points and decontamination operation space considered during decommissioning in the design
	D3	Proportion of recyclable protection materials	The proportion of recyclable materials among the protection materials selected in the design
	D4	Guidance for classified disposal of decommissioning waste	The detail degree of classified disposal requirements for different types of protection waste specified in the design documents
	D5	Adaptability for site reuse after decommissioning	The degree to which the site is convenient to be transformed into other non-radiation uses after decommissioning, reducing secondary transformation costs
	D6	Pre-assessment design for decommissioning environmental impact	The perfection degree of pre-assessment of the impact of the decommissioning process on the surrounding environment considered in the design stage
	D7	Controllability of decommissioning treatment cost	The degree to which the decommissioning treatment cost is controlled within a reasonable range from the perspective of the whole life cycle in the design scheme

The admission review is a necessary prerequisite step. Only after passing the review can one proceed to the scoring stage. The scoring is conducted on a 100-point scale. The weights of the four criterion layers remain as originally set in the research: planning and design compatibility 0.48, construction feasibility 0.18, operation and maintenance sustainability 0.24, and decommissioning environmental friendliness 0.10. The scoring criteria still use a 5-level classification: 90–100 (excellent), 75–89 (good), 60–74 (qualified), 40–59 (unqualified and requires rectification), 0–39 (serious defects require redesign).

### 2.3. Quantification of indicators and data collection

The scoring system adopts a 100-point scale. These indicators are classified into 5 grades based on the degree to which they meet the requirements: 90–100 points indicate excellent performance, fully meeting the requirements with a high degree of redundancy; 75–89 points indicate good, meet the requirements of the specification and adapt to the actual needs of the project; 60–74 points indicate qualified performance, basically meeting the minimum requirements of the specification; 40–59 points indicate unqualified performance, with some non-compliance with the specification requirements, requiring rectification; 0–39 points indicate poor performance, with serious radiation safety hazards, and the design must be redone. In order to complete the quality assessment, in the evaluation of design document review indicators, documents such as design specifications, shielding calculation documents and construction drawings will be reviewed to obtain the specific degree of completion of the indicators <sup>[7]</sup>. Calculate the design margin of the main shielding layer thickness, the shielding level of the protective door, and other adaptability indicators, and recalculate the deviation between the design parameters and the theoretical requirement values. Simulation analysis and simulation derivation were also used to evaluate the feasibility of construction and the ease of demolition, and experts in the fields of construction, operation and decommissioning disposal were invited to score <sup>[8]</sup>.

## 3. Evaluation results and model application

### 3.1. Indicator evaluation and weight calculation

In this study, the subjective and objective fusion weight assignment method combining analytic hierarchy process (AHP) and entropy weight method was used. According to the results of expert consultation, the judgment matrix of each level index was constructed, and 20 experts were invited to compare the relative importance of the indicators at the same level, and the 1–9 scale method was used to score. The subjective weights of each indicator were calculated using the YAAHP software and consistency tests were conducted. The results showed that the consistency ratio CR of all judgment matrices was less than 0.1, meeting the consistency requirements. The weight distribution is based on the dual logic of expert consensus and the analysis of the risk contribution throughout the entire life cycle. The subjective weights of the four criterion layers were as follows: planning and design adaptability 0.48, construction feasibility 0.18, operation and maintenance sustainability 0.24, and decommissioning environmental protection 0.10. It can be seen that the quality of the planning and design stage has the greatest impact on the overall project quality <sup>[9]</sup>.

The design data of 30 radiation protection projects in general hospitals completed in the past three years were collected as samples. The scoring results of 27 indicators were standardized, and the information entropy of each indicator was calculated. The objective weight was determined according to the information entropy. The smaller the information entropy, the higher the discrimination of the indicator and the greater the weight.

Finally, the comprehensive weight was obtained through linear weighted combination, and the calculation formula is:

$$w_i = \alpha \cdot w_{i1} + (1 - \alpha) \cdot w_{i2}$$

Where  $w_{i1}$  is the subjective weight obtained by analytic hierarchy process,  $w_{i2}$  is the objective weight obtained by entropy weight method,  $\alpha$  represents the preference coefficient of subjective weights. Based on literature

analysis and industry consensus, in this study, the coefficient is set at 0.6., that is, the subjective weight accounts for 60%, and the objective weight accounts for 40%, taking into account both expert experience and actual data characteristics. The calculation results of the comprehensive weights for each indicator are shown in **Table 3**.

**Table 3.** Comprehensive weight table of evaluation indicators

Criterion layer (Weight)	Index	Subjective weight	Objective weight	Comprehensive weight
Planning and design adaptability (0.48)	A1	0.152	0.138	0.146
	A2	0.136	0.142	0.138
	A3	0.124	0.118	0.122
	A4	0.118	0.125	0.121
	A5	0.095	0.087	0.092
	A6	0.087	0.092	0.089
	A7	0.076	0.081	0.078
	A8	0.072	0.068	0.07
	A9	0.065	0.073	0.068
	A10	0.075	0.076	0.076
Construction feasibility (0.18)	B1	0.285	0.262	0.276
	B2	0.212	0.228	0.218
	B3	0.198	0.205	0.201
	B4	0.175	0.183	0.178
	B5	0.13	0.122	0.127
Operation and maintenance sustainability (0.24)	C1	0.224	0.236	0.229
	C2	0.186	0.178	0.183
	C3	0.175	0.182	0.178
	C4	0.142	0.135	0.139
	C5	0.121	0.128	0.124
	C6	0.088	0.095	0.091
	C7	0.064	0.046	0.056
Decommissioning environmental friendliness (0.10)	D1	0.312	0.298	0.306
	D2	0.265	0.278	0.27
	D3	0.174	0.182	0.177
	D4	0.135	0.146	0.139
	D5	0.114	0.096	0.108

The design quality of radiation protection engineering to be evaluated is taken as the matter element R, which is composed of three elements: evaluation object N, evaluation feature C and characteristic quantity V, namely  $R=(N,C,V)$ . Among them, C corresponds to 27 evaluation indicators, and V corresponds to the score values of each indicator. The evaluation grades are divided into five levels: excellent ( $N_1$ )、good ( $N_2$ )、qualified ( $N_3$ )、poor ( $N_4$ )、very poor ( $N_5$ ) , with the corresponding value ranges being  $< 90, 100 >$ ,  $< 75, 89 >$ ,  $< 60, 74 >$ ,  $< 40, 59 >$ , and  $< 0, 39 >$ , respectively. The evaluation range is the total range of indicator values for all evaluation grades, that is,  $< 0, 100 >$ . The correlation degree reflects the degree to which the evaluated object belongs to a certain evaluation grade. The calculation formula is:

$$K_j(v_i) = \begin{cases} \frac{\rho(v_i, X_{ji})}{|X_{ji}|}, & v_i \in X_{ji} \\ \frac{\rho(v_i, X_{ji})}{\rho(v_i, X_p) - \rho(v_i, X_{ji})}, & v_i \notin X_{ji} \end{cases}$$

Here,  $\rho(v_i, X_{ji})$  represents the distance from point  $v_i$  to the interval  $X_{ji}$ ,  $\rho(v_i, X_p)$  represents the distance from point  $v_i$  to the sub-interval  $X_p$ , and  $|X_{ji}|$  is the length of the interval  $X_{ji}$ . Calculate the comprehensive correlation degree: Based on the comprehensive weights of each indicator, calculate the comprehensive correlation degree of the evaluated object to each evaluation level:

$$K_j(N) = \sum_{i=1}^n w_i \cdot K_j(v_i)$$

Where  $w_i$  represents the comprehensive weight of the  $i$ -th indicator.

Determine the evaluation level: If  $K_{j_0}(N) = \max\{K_j(N)\}$ , then the evaluated object belongs to level  $j_0$ . To further reflect the position of the evaluated object within the corresponding level, the characteristic value of the level variable can be calculated:

$$j^* = \frac{\sum_{j=1}^m j \cdot |K_j(N)|}{\sum_{j=1}^m |K_j(N)|}$$

The closer  $j^*$  is to a certain level's value, the more the evaluated object is close to the level's standard.

In order to verify the actual application effect of the model, five radiation protection projects that had completed the completion acceptance and had more than 3 years of operation and maintenance data were selected as verification samples. The model constructed in this study was evaluated by the traditional compliance review method, and the matching degree between the two evaluation results and the actual operation effect was compared [10].

The verification results show that the traditional compliance review method rated all five samples as "excellent", while the evaluation results of the proposed model indicate that 3 samples were rated as "excellent" and 2 samples were rated as "good". It can be seen that compared with the traditional method, this research model can more accurately identify potential risks.

## 4. Conclusion

This paper constructs a design life cycle assessment model based on the concept of the entire life cycle. It assesses the design quality from comprehensive perspectives such as compliance and long-term effectiveness. The research results can provide scientific quality monitoring tools for relevant departments, enhance the overall level of protective engineering, and ensure safety.

## Disclosure statement

The author declares no conflict of interest.

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