Methods and Applications

Measuring the Capability of Biological Incident Rescue Teams in China: A Fuzzy Analytic Hierarchy Process Based Model — Tianjin Municipality, China, 2022–2023

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ABSTRACT

Introduction: The swift advancement of biotechnology has presented both opportunities and challenges to our society, thrusting biosafety to the forefront of concern. Consequently, the evaluation of rescue capabilities in the event of a bioterrorism incident becomes of paramount importance. Currently, there is a notable absence of specific measurement criteria and a comprehensive evaluation system. This paper aims to establish a systematic approach towards assessing emergency response capabilities in the context of bioterrorism incidents.

Methods: We employed an enhanced Delphi methodology to establish an index evaluation framework. Subsequently, the weight of the judgment matrix was ascertained via the application of the fuzzy comprehensive evaluation approach. This led to the creation of a fuzzy comprehensive evaluation model for bioterrorism rescue capability.

Results: A modified Delphi study was conducted involving 11 experts across two rounds, achieving a response rate of 100%. The Kendall coordination coefficients recorded in the first and second rounds were 0.303 and 0.632, respectively ($P<0.05$). Upon comprehensive analysis involving score, coefficient of variation, and full score ratio, we distinguished five primary indicators and 25 secondary indicators. Subsequently, an evaluation model was developed based on the Analytic Hierarchy Process (AHP) tailored to assess the response to a rescue from bioterrorism.

Discussion: The expert panel confirmed consensus on all aspects of the model, validating its comprehensive content. The succeeding course of action involves converting the assessment model to a measurable scale, affirming its functionality, and implementing it in practical evaluation tasks to further enhance the capabilities of the biological incident rescue team.

Recent years have seen a rapid increase in both population density and personnel flow, with parallel advancements in biotechnology and information technology. This has resulted in an increasingly complex international biosafety situation, amplified by the potential misuse of biotechnology in bioterrorism activities, posing significant threats to public security and international order (*1*).

According to the Global Terrorist Database, there have been approximately 200,000 terrorist attacks worldwide from 1981 to 2021, 41 of which involved bioterrorism. These attacks led to 11 fatalities and 813 disease-related cases (*2*). Given this context of prevailing biosecurity concerns, current rescue capabilities are proving insufficient to meet the actual requirements.

Emergency rescue teams and disaster emergency management operations pertaining to biological events are faced with challenges such as inadequate training experience, response capabilities, and a lack of uniform criteria for ability evaluation. Challenges also include an inconsistency in the quality of rescue teams, as well as sluggish team construction. With bioterrorism presenting as a low-probability, high-risk event, there is a scarcity of research literature on the subject. The prevalent assessment system for rescue capability concentrates more on tsunamis, earthquakes, and similar events (*3*).

Additionally, the prevailing research relies heavily on the Delphi method. In this method, due to the subjectivity of experts and the ambiguity of indicators, the weights assigned to each indicator are unclear. Consequently, it is challenging to represent the significance of key indices with precise values, leading to less accurate evaluation outcomes (*4*).

Therefore, the urgent need for a rigorous evaluation system for the response and rescue in bioterrorism events cannot be overstated.

METHODS

We utilized the Delphi method to construct the indicator system in this research study and deployed the boundary value method for indicator selection. Once identified, we calculated the weight of each index via the analytic hierarchy process and utilized these calculations to construct a fuzzy comprehensive evaluation model. Microsoft Excel (Version 2016; Microsoft, New York, USA) and SPSS software (Version 22.0; IBM, New York, USA) were employed for all statistical analyses. Further details regarding these methodologies are furnished in the Supplementary Material (available in https://weekly.chinacdc.cn/).

Semi-Structured Interview

We elicited insights from experts affiliated with the Chinese Academy of Military Medical Sciences, the Chinese Center for Disease Control and Prevention, and various academic institutions, through comprehensive semi-structured interviews prior to formal correspondence. This approach facilitated dynamic and adaptable dialogues, allowed for customized inquiries according to unique needs, and helped to foster rapport with the interviewees.

Questions were drafted in accordance with the Guidelines for Capacity Building and Grading Evaluation of National Urban Rescue Teams (draft), exploring their perceptions of bioterrorism events, the core responsibilities of rescue teams, and interdepartmental collaboration, among other relevant topics.

After assimilating the study's background, objectives, and methods, the experts offered extensive inputs and recommendations through the provisional indicator framework. Consequently, we refined and improved the draft indicator framework by integrating these expert opinions to guide the subsequent development of the questionnaire.

Expert Selection

Considering the suitability of the Delphi method and the field-specific requirements of the study, we selected 11 senior professionals as expert participants. These experts were pulled from various domains such as public health, emergency management, or epidemiology. They were drawn from several organizations, including the Chinese Center for Disease Control and Prevention, People's Liberation Army, People's Armed Police Force, hospitals, and universities, as well as aggregated from experts at the national and provincial levels, utilizing purposive sampling.

All chosen expert participants had accumulated over five years of experience in emergency management, disaster-related occupations, or on the subject of research. Each held an associate senior professional title or superior, obtained a minimum of a bachelor's degree, and was acknowledged for conducting relevant research in their fields. All expert participants voluntarily contributed to the study with good compliance and gave the assurance of their dedication until the study consultations were concluded.

Questionnaire Design

Based on the framework derived from literary analysis and expert interviews, the initial draft of the expert consultation questionnaire was developed. This draft showcased the underlying context, explanations pertinent to the index system, assessment of index importance and familiarity, and expert-specific data. Following the first round of expert consultation, the questionnaire was revised to reflect the outcome. The second version incorporated comprehensive scoring averages, coefficients of variance, full score ratios, and each index's expert opinion from the initial consultation round for reference. Experts assigned weights to every index using a 5-point scale.

RESULTS

The Delphi survey was carried out between August 19 and September 20, 2022. We invited a total of 15 specialists from national, provincial, and municipal disease control and prevention centers, health administrative departments, scientific research institutions, and allied domains. After reaching out via email, 11 experts expressed their interest and confirmed their availability to participate. Subsequently, we communicated with these experts through emails soliciting their feedback on the indicator content. This process was repeated for the second round of consultation. Ultimately, all 11 invited experts successfully participated in the full Delphi survey, achieving a response rate of 100%. Information detailing the participant's demographic characteristics can be found in Table 1.

Through a combination of literature review, semi-structured expert interviews, and consideration of China's unique national conditions, the tasks of emergency rescue teams in bioterrorism incidents were

TABLE 1. The characteristics of experts in the panel.

Characteristics	Demographics	Count (*n*=11)
Gender	Male	9
	Female	2
Age (years)	35–40	1
	41–45	5
	46–50	2
	Over 50	3
Specialty	University academic	5
	Physician	4
	Disaster management	2
Title of the job	Professor	9
	Associate professor	2
Education level	Master	3
	Doctoral/PhD	8
Work area	Public health	4
	Disaster rescue	1
	Emergency management	5
	Rescue technology	1
Working experience (years)	5–10	2
	11–15	2
	16–20	4
	Over 20	3

distilled into four main responsibilities. These include: controlling exposure within the population and halting transmission to prevent further infection; rapidly curbing the situation through establishing isolation areas, conducting epidemiological investigations, and decontaminating affected regions; identifying biological pathogens and incident types to provide an essential basis for medical services; and mitigating harmful consequences while ensuring thorough on-site recovery. The expert interview questionnaire is presented in Supplementary Table S1 (available in https://weekly.chinacdc.cn/).

In two iterations of expert consultation, our team computed and scrutinized the expert authority coefficient as well as the consistency degree. The given experts' judgment basis (Ca) values were 0.895 and 0.877 respectively, while the familiarity degree (Cs) values stood at 0.836 and 0.855 in respective order. The expert authority coefficient (CR), on the other hand, was consistently at 0.866, thereby satisfying the Cr≥0.7 criterion. This implies a high level of expert authority and, by extension, the reliability of the expert consultation process (Supplementary Table S2, available in https://weekly.chinacdc.cn/).

The Kendall coordination coefficient demonstrated a shift from 0.303 ($P<0.05$) to 0.632 ($P<0.05$). This increase, falling within the 0.6 to 0.8 range, signifies a high degree of consistency and a low level of significance, thereby indicating a high level of independence among the indicators. Coefficients of variation for the two evaluations were observed to be 0.106 and 0.063 respectively, both under the threshold of 0.25. This detail suggests that expert opinions were notably aligned, yielding consistent evaluation results and validating the credibility of the index system. The results of the Kendall coordination coefficient test can be found in Supplementary Table S3 (available in https://weekly.chinacdc.cn/).

Based on expert feedback and scoring, the boundary value for each index was computed (Supplementary Table S4, available in https://weekly.chinacdc.cn/). The chosen indexes were then consolidated and accordingly adjusted, following expert recommendations. This process eventually yielded five primary indicators and twenty-five secondary indicators for assessing a bioterrorism rescue team's capability. The significance of these level indexes within the developed evaluation system was gauged in two rounds of expert consultations and group discussions (Supplementary Table S5, available in https://weekly.chinacdc.cn/). Importance was ascertained based on the influence of certain factors on bioterrorism rescue capabilities, thereby determining the final weight of each index (Table 2).

DISCUSSION

To the best of our knowledge, this represents the first study conducted in China that employs the Delphi survey and the Analytic Hierarchy Process (AHP) to explore expert perspectives, with the aim of establishing a capability evaluation model for biological rescue teams. The derived evaluation model from our study can serve as a useful reference instrumental in the development and enhancement of rescue team capabilities. Furthermore, it provides a robust tool for evaluating the efficacy of rescue teams in the context of bioterrorism incidents.

The formation of expert panels is integral to the Delphi method. Currently, a well-defined standard for the evaluation of bioterrorism response capabilities does not exist, hence the necessity to establish one through the guidance of an expert panel (*5*). In the current study, we assembled the panel from a cross-section of professionals in China, including university

TABLE 2. First and second-level index weight distribution and testing.

Indicators	Weights	Consistency check
First Level Indicator		
Capacity building of rescue team A	0.13200	CI=0.056 RI=1.120 CR=0.050 Maximum characteristic value =5.225
Emergency response factors of rescue team B	0.23053	
Rescue team emergency rescue factors C	0.48353	
Rescue team evacuation D	0.06378	
Recovery evaluation factors of rescue team E	0.09016	
Second Level Indicator		
Emergency response mechanism A1	0.16734	CI=0.071 RI=1.120 CR=0.064 Maximum characteristic value =5.285
Team building A2	0.09408	
Material and equipment A3	0.46158	
Training and exercises A4	0.20207	
Team composition A5	0.07493	
Organize, direct and coordinate B1	0.19634	CI=0.067 RI=0.890 CR=0.075 Maximum characteristic value =4.201
Emergency response mechanism B2	0.35045	
Information acquisition and analysis B3	0.33875	
Risk communication B4	0.11447	
Control of exposed population C1	0.06259	CI=0.088 RI=1.410 CR=0.062 Maximum characteristic value =8.615
Isolation and quarantine C2	0.06963	
Field survey and sampling C3	0.23293	
On-site decontamination C4	0.16486	
Real-time monitoring C5	0.04847	
Emergency medical rescue C6	0.08167	
Epidemiological investigation C7	0.11844	
Detection and analysis C8	0.22141	
Research and evaluation D1	0.58126	CI=0.002 RI=0.520 CR=0.004 Maximum characteristic value =3.004
On-site inspection D2	0.30915	
Withdraw the team D3	0.10959	
Physical examination E1	0.15667	CI=0.084 RI=1.120 CR=0.075 Maximum characteristic value =5.336
Psychological intervention E2	0.21289	
Recovery of equipment E3	0.30692	
Mitigation evaluation E4	0.06353	
Evaluation of effectiveness E5	0.26000	

Abbreviation: CR=expert authority coefficient; CI=coincidence indicator; RI=random consistency index.

academicians, hospital executives, and researchers from the CDC. These individuals have established careers in public health, emergency management, and disaster relief and possess a vast array of knowledge in terms of managerial and technical roles. Equipped with a deep understanding and distinctive perspectives on rescue operations, they have generated an evaluative model in this study which can therefore be effectively deployed in critically assessing the management, personal quality, and operational competence of bioterrorism response teams.

Biological incidents, such as disease epidemics or biohazard spills, pose substantial threats to public health and safety. Consequently, the effective execution of on-site mitigation activities is vital to lessen these events' impact and safeguard lives. These activities extend beyond routine crowd management and decontamination to include critical aspects such as sampling and detection. The quality of the on-site sampling process is paramount as it influences detection accuracy. Given the novelty and diversity of biological warfare agents, their identification relies on both prompt on-site detection and meticulous laboratory monitoring. Optimal outcomes necessitate rapid field detection balanced with rigorous laboratory scrutiny. The nexus between these two aspects deserves due consideration as the detection outcomes significantly influence on-site management strategies and decision-making processes.

Since the severe acute respiratory syndrome (SARS) outbreak in 2003, China has primarily directed its emergency response capability evaluation system towards public health emergencies (*6*). The country's experience with events like the H1N1 influenza pandemic and the coronavirus disease 2019 (COVID-19) pandemic further accentuates the necessity of a robust and efficient emergency response capability evaluation framework.

Presently, there appears to be an absence of rescue quality assessment. This includes evaluations of comprehensive procedures, the health and equipment deterioration of team personnel, the anticipatory control of the incident, as well as on-site and ultimate controls. To enhance impartiality, third-party evaluations should be contemplated. This approach will not only expedite the incident's resolution but will also bolster capacity building within rescue teams.

Team building encompasses the entire cycle of entry, operation, management, and departure of team members. Strategic investment in talent can produce the most enduring contribution to the quality of rescue efforts (*7*). As such, it is critical to augment funding towards talent development, and to implement regular, capability-focused training and upskilling that align with practical needs, thus fostering sustainable human development. Notably, in the context of China, the role of cross-sectoral collaboration in team building demands acknowledgement, and needs to be incorporated in the initial stages of team design.

This study, like any other, has limitations that must be recognized. First, due to the infrequency of bioterrorism events and a shortage of related research, we attempted to compose an expert panel for the Delphi investigation by selecting individuals with significant research relevance. Nevertheless, the number of experts chosen was limited, and none were from outside the domestic scope. Secondly, there is a lack of research evaluating the capabilities of rescue teams, which suggests a potential avenue for future research expansion.

In summary, consensus was achieved on all indicators of the model by the panel of experts, demonstrating good content validity for the overall scale. The subsequent phase involves transforming this evaluation model into a scalable format for distribution via a questionnaire. Moreover, we plan to examine the feasibility of applying this method in other medical capacity assessments, particularly within the realm of emergency medical rescue teams for emerging infectious diseases. Prior to its utilization in actual assessment work, the practicality and implementability of this model must be analyzed in the context of evaluating the capability of a biological event rescue team.

Conflicts of interest: No conflicts of interest.

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SUPPLEMENTARY MATERIALS

Detailed Methods of the Study

In light of the applicability of the Delphi method in this study, 11 prominent experts were purposefully selected from numerous fields including public health, emergency management, epidemiology, and others. These specialists were drawn from various institutions such as the Chinese Center for Disease Control and Prevention, the People's Liberation Army, the People's Armed Police Force, hospitals, and universities. Additionally, seasoned experts at national, provincial, and municipal levels were included. All involved had no less than five years of experience in fields related to emergency management, rescue work, or relevant research. Moreover, the experts held at least an associate senior professional title, possessed a bachelor's degree or higher, and had respectable recognition in their research fields. Participation was voluntary with all participants demonstrating strong compliance and commitment to remain involved until the conclusion of the study.

Using the analytic hierarchy process to determine weight: This study employed the analytic hierarchy process (AHP), using scales of 1–9 judgment matrices (Supplementary Table S5) to conduct pairwise comparisons of same-level elements. These comparisons were then used to construct the judgment matrix, calculate the maximum eigenvalue, and perform a consistency test on the judgment matrix of the equivalent level. The primary formula for pathogenicity testing and ranking was as follows:

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} A =$$

$$CI = (\lambda max - n)/(n-1) \quad (1)$$

A is the judgment comparison matrix, while λmax is the maximum eigenvalue of the judgment matrix. n is the order of the judgment matrix, whereas confidence interval (CI) is the consistency of the matrix. The closer the value that CI is to 0, the stronger the consistency of the judgment matrix, and the weight value of the index being allocated reasonably. RI is the random consistency index, which is used to measure the size of CI. The standard value of RI is obtained according to the order of the matrix. expert authority coefficient (CR) is the test coefficient, and when $CR<0.1$, A is judged to have satisfactory consistency.

Establishing a comprehensive fuzzy evaluation model: According to the established evaluation index system, on the basis of AHP, the fuzzy comprehensive evaluation method was used to establish the corresponding comprehensive evaluation factor set. To determine the evaluation index and comment set: U = {A, B, C, D, E}, A = {A1, A2, A3, A4, A5}…

The evaluation set and corresponding score set V for comprehensive evaluation were established. The evaluation level is n kinds of decisions on the state of each index, V = {V1, V2, V3, ... Vn}, where Vi represents the ith

SUPPLEMENTARY TABLE S1. Semi-structured interview questions.

Number	Question
1	What are the main hazards of a bioterrorist attack? What is the difference between nuclear and chemical events?
2	What rescue teams for bioterrorism are there? Who is it made up of? What institutions are they based on?
3	How are rescue teams and other departments such as police/emergency departments divided? What is the main job of the rescue team against bioterrorism? What's the difference from other rescue teams?
4	What is the main direction in the capacity building of the rescue team? What is the most important of these?
5	What are the specific tasks in the prevention and preparation phases of the rescue team?
6	What do rescue teams need to accomplish during the response and disposal phases? Which step is the most important?
7	What equipment do rescue teams use to transport people to hospitals? How is the target or designated hospital selected?
8	Is there a standard for rescue team personnel to classify the dead at the scene? What are the criteria?
9	Is there any understanding of the construction of the evaluation index system for the work quality of rescue teams? What are the indexes?
10	What is the research direction of the work quality evaluation and capacity building of the rescue team?

SUPPLEMENTARY TABLE S2. Expert authority coefficient.

Rounds	Ca	Cs	CR
Round 1	0.895	0.836	0.866
Round 2	0.877	0.855	0.866

Abbreviation: Ca=experts' judgment basis; Cs=familiarity degree; CR=authority coefficient.

evaluation result, i = 1, 2, 3, ... , *n*, and *n* is the total number of evaluation results. In this paper, the evaluation levels were divided into five grades: very important, relatively important, general, less important and very little important.

V = {V1, V2, V3, V4, V5}

= {very important, relatively important, general, less important, very little important}

= {5, 4, 3, 2, 1}

The degree of membership of each index relative to the evaluation set was computed, and the membership degree of the ith influence factor in the set U to the jth element in the evaluation set V was designated as rij, with a range from 0 to 1. Given m influencing factors and n evaluation elements, the fuzzy relationship matrix R can be defined as follows:

$$R = (rij)mn = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} \\ \vdots & \vdots & \ddots & \vdots \\ r_{imi1} & r_{imi2} & \cdots & r_{imik} \end{bmatrix} \quad (2)$$

We established a comprehensive evaluation model to calculate the overall score of the system, taking into account the weight value wij for each hierarchical factor as determined by AHP. A comprehensive assessment was performed on the single index, resulting in the computation of the fuzzy relation evaluation vector Bi.

$$Bi = wiR = (wi1, wi2, wimi)\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} \\ \vdots & \vdots & \ddots & \vdots \\ r_{imi1} & r_{imi2} & \cdots & r_{imik} \end{bmatrix}$$

$$= (bi1, bi2, \ldots bik), i = (1, 2, \ldots m)$$

Progressively, the evaluation model was developed. Subsequently, both the fuzzy evaluation matrix B and the equivalent score F were computed as follows:

$$B = wR$$

$$F = BVT$$

Statistical analysis: Data were organized using Microsoft Excel (Version 2016; Microsoft, New York, USA), while SPSS software (Version 22.0; IBM, New York, USA) was utilized for computing the expert positive coefficient (questionnaire recovery rate) and the coordination coefficient W of expert opinions. A non-parametric test was conducted on K relevant samples of W value, with $P<0.05$ suggesting a tendency towards consistent expert scores. The Cr was computed based on the experts' judgment basis (Ca) and familiarity degree (Cs) using the Formula Cr = (Ca + Cs)/2. An authority coefficient >0.70 indicated high predictive accuracy and dependable consultation results. We also calculated the mean ± standard deviation and coefficient of variation on the concentration degree of indicators at all levels (comprehensive scores) of expert opinions. Indicators were deemed highly acceptable if the standard deviation of the importance score of indicators was less than 1 and the coefficient of variation was less than 0.2.

The results of the Kendall Coordination Coefficient test are displayed in Supplementary Table S3. In the initial phase, a Kendall Coordination Coefficient of 0.303 ($P<0.05$) was observed, suggesting a generalized yet relevant evaluation consistency among the 11 reviewers, as the coefficient fell between 0.2 and 0.4. In the subsequent round, the Kendall Coordination Coefficient increased to 0.632 ($P<0.05$), reflecting a strong degree of consistency as the value lay between 0.6 and 0.8. This implied a low level of significance and, consequently, a high degree of independence among the indicators. Further, the variation coefficients in these two rounds were 0.106 and 0.063, respectively, remaining below the threshold value of 0.25, thereby denoting a significant concentration in expert opinions. This convergence of expert perspectives indicated consistent evaluation outcomes and affirmed the reliability of the index system.

SUPPLEMENTARY TABLE S3. Kendall coefficient test.

Rounds	Kendall coordination coefficient	Statistics value	Significance	Coefficient of variation
Round 1	0.303	93.457	0	0.106
Round 2	0.632	201.497	0	0.063

Based on expert feedback and scores, we calculated the boundary value for each index (Supplementary Table S4). Indices failing to meet the screening conditions were assessed and subsequently eliminated. In accordance with expert guidance, we suitably consolidated and adjusted the selected indices. Ultimately, we established five primary indicators and 25 secondary indicators as evaluation criteria for assessing the capability of a bioterrorism response team.

SUPPLEMENTARY TABLE S4. Index screening of critical value indicators.

Scale		Composite score			Coefficient of variation			Full score ratio		
		Mean value	Standard deviation	Eligibility criteria	Mean value	Standard deviation	Eligibility criteria	Mean value	Standard deviation	Eligibility criteria
Round 1	First-level indicators	4.56	0.44	≥4.12	0.10	0.06	≤0.16	0.91	0.09	≥0.82
	Second-level indicators	4.59	0.15	≥4.44	0.11	0.04	≤0.15	0.92	0.05	≥0.87
Round 2	First-level indicators	4.53	0.17	≥4.35	0.07	0.04	≤0.11	0.91	0.11	≥0.79
	Second-level indicators	4.83	0.18	≥4.65	0.06	0.04	≤0.10	0.97	0.06	≥0.91

SUPPLEMENTARY TABLE S5. Scaling the judgment matrix.

Scale	Definition	Meaning
1	The same importance	The two indicators are of the same importance.
3	Slightly important	Index i is slightly more important than index j.
5	Obviously important	Index i is obviously more important than the index j.
7	Strongly important	Index i is strongly more important than index j.
9	Absolutely important	Index i is absolutely more important than index j.
2,4,6,8	The median value of the above adjacent judgment.	
	If the ratio of the importance of the index i and the index j is a_{ij}, then the ratio of the factor to the importance of the $a_{ij} = 1/a_{ji}$. Factor is a_{ij}=1/a_{ji}.	