

Study on Risk Identification and Safety Grading Evaluation of Repetitive Diving for Leisure Divers

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Abstract: In this study, a safety classification model based on analytic hierarchy process (AHP) and fuzzy comprehensive evaluation method (FCE) was established to prevent and control the risk of repetitive diving for leisure divers. Sixteen key risk factors were selected by literature analysis and Delphi method, covering four criteria levels: physiological state, diving operation, interval accumulation and environmental equipment, among which the maximum diving depth, underwater residence time and water surface interval time were the core indicators. AHP is used to determine the weight of each factor, and FCE is combined to realize the quantitative evaluation of safety level. The model is verified by 35 real repetitive diving cases, and the results show that the coincidence rate with expert evaluation is 82.9%, which can effectively distinguish low-to-high risk scenarios. The research shows that the core of repetitive diving safety lies in standardizing diving operation, optimizing interval management and paying attention to individual physiological state. This model provides a scientific tool for the course design of diving training institutions, the self-evaluation of repetitive divers and the industry supervision, and has important practical value for reducing repetitive diving accidents and promoting the sustainable development of diving.

Keywords: Leisure Diver; Repetitive Diving Risk; Safety Classification; Analytic Hierarchy Process; Fuzzy Comprehensive Evaluation.

1. Introduction

With the continuous expansion of diving destinations, the increasing popularity of diving equipment and the promotion of diving experience by social media, more and more people include leisure diving in their leisure and entertainment choices. However, with the rapid expansion of the participant base, diving safety accidents are also on the rise. Decompression sickness (DCS), arterial gas embolism (AGE), drowning and equipment failure are the main causes of leisure diving accidents [1]. How to effectively identify and control diving risks has become an important issue to be solved urgently in the field of diving safety management.

Repetitive diving, that is, when the diver still has the "residual nitrogen" of the previous diving in his body after the last diving, he dives again. At present, most of the diving safety research and training systems are designed with "beginner's introduction" as the core, and the special risk assessment and safety management measures for repetitive divers are still quite scarce. In view of this, this study systematically identifies the key risk factors in the process of repetitive diving for leisure divers through the methods of literature analysis, expert consultation and questionnaire survey. Analytic Hierarchy Process (AHP) is used to determine the relative weight of each risk factor, and a repetitive diving safety grading evaluation model is constructed by combining fuzzy comprehensive evaluation method (FCE). Finally, according to the evaluation results, the safety management suggestions of repetitive diving under different risk levels are put forward, which provides scientific reference for the curriculum design of diving training institutions, the self-evaluation of repetitive diving practitioners and the formulation of industry supervision standards. The development of this study not only helps to fill the academic gap in the subdivision of repetitive diving risk,

but also has direct practical application value, which is of positive significance for reducing the incidence of repetitive diving accidents and promoting the sustainable and healthy development of leisure diving.

2. Research Method

2.1. Research Design

The research adopts three-stage progressive research design: risk factor identification, index weight determination and safety grading evaluation. Firstly, through the method of literature analysis and expert consultation, the key risk factors in the process of repetitive diving of leisure divers are systematically identified, and the safety evaluation index system of repetitive diving is constructed. Then use AHP to determine the relative weight of indicators at all levels; Finally, FCE is introduced to establish the safety grading evaluation model of Repetitive Diving, and the comprehensive evaluation of safety grading of Repetitive Diving activities is realized.

2.2. Risk Factor Identification Stage

(1) Literature analysis

Systematic retrieval of domestic and foreign academic literature and industry reports on leisure diving safety accidents, DCS risk factors and repetitive diving safety. Focus on the unique risk factors in repetitive diving scenario, such as residual nitrogen after previous diving, water surface interval, cumulative effect of multi-day continuous diving and so on [2]. Previous studies have shown that the reduction of repetitive diving times and the shortening of water surface interval are significantly related to DCS risk [3]. The purpose of literature analysis is to build an initial list of risk factors and provide basic materials for subsequent expert consultation.

(2) Expert consultation (Delphi method)

On the basis of the initial list of risk factors formed by literature analysis, the factors are screened and confirmed by Delphi Method [4]. The specific operation is as follows:

1) Invite 15 ~ 20 experts with rich diving teaching experience or diving medical background to form an advisory group, covering diverse backgrounds such as diving coaches, diving medical doctors, diving researchers and senior leisure divers.

2) Two rounds of expert consultation were conducted. In the first round, an open questionnaire was used, and experts were asked to supplement, merge or delete the initial list of risk factors, and preliminarily judge the importance of each factor; In the second round, a structured questionnaire was used, and experts were asked to compare and judge the screened factors on a scale of 1 ~ 9.

3) When the coordination coefficient of expert opinions (Kendall's W) reaches a statistically significant level ($p < 0.05$), it is considered that the expert opinions tend to be consistent and the consultation is terminated.

After screening using the Delphi method, the indicator system for regenerative diving safety evaluation was finally determined, including three levels: target layer, criterion layer, and indicator layer.

2.3. Construction of Safety Grading Evaluation Model

2.3.1. Determination of Index Weight by AHP

(1) Establish a hierarchical structure model

The problem of repetitive diving safety evaluation is decomposed into target layer, criterion layer and index layer to form a hierarchical structure.

(2) Constructing a judgment matrix

According to the results of pairwise comparison in expert consultation, the relative importance of each factor at the same level relative to a factor at the previous level is quantified. Saaty 1 ~ 9 scale method is adopted [5], with scale 1 indicating that two factors are equally important, scale 9 indicating that the former is extremely important than the latter, and so on. Construct a judgment matrix $A=(a_{ij})_{n \times n}$, where a_{ij} represents the importance of factor i relative to factor j , and satisfies $a_{ij} > 0$, $a_{ij} = 1/a_{ji}$, and $a_{ii} = 1$.

(3) Calculating a weight vector

Calculate the maximum eigenvalue $\lambda_{\max}$ of the judgment matrix and its corresponding normalized eigenvectors $W=(w_1, w_2, \dots, w_n)^T$ using the root mean square method or sum product method, which are the weights of each factor [6]. The core formula for weight calculation is:

$$w_i = \frac{\sqrt[n]{\prod_{j=1}^n a_{ij}}}{\sum_{k=1}^n \sqrt[n]{\prod_{j=1}^n a_{kj}}} \quad (1)$$

Among them, w_i is the weight of the i -th factor, n is the order of the judgment matrix, and a_{ij} is the element in the i -th row and j -th column of the judgment matrix. The numerator is the geometric mean of all elements in the i -th row, and the denominator is the sum of the geometric means of all rows, ensuring normalization of the weight vector ($\sum w_i = 1$).

(4) Consistency check

To ensure the logical consistency of expert judgments, it is necessary to perform consistency checks on the judgment matrix. Firstly, calculate the consistency metric:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (2)$$

Among them, $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, and n is the order of the matrix. The closer the CI value is to 0, the better the consistency.

Then calculate the consistency ratio:

$$CR = \frac{CI}{RI} \quad (3)$$

Among them, RI is a random consistency index, and its value varies with the matrix order n . When $n=1 \sim 9$, RI values are 0, 0, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41, and 1.45, respectively. When $CR < 0.10$, it is considered that the consistency of the judgment matrix is acceptable; Otherwise, experts need to readjust the judgment matrix.

2.3.2. FCE Builds a Hierarchical Evaluation Model

(1) Determine the evaluation factor set and comment set

Let the set of evaluation factors $U=\{u_1, u_2, \dots, u_m\}$, which are the m risk factors in the indicator layer of the AHP model. Let the comment set $V=\{v_1, v_2, v_3, v_4, v_5\}$, corresponding to five security levels, such as {low risk, low risk, medium risk, high risk, high risk}.

(2) Determine the membership matrix

Invite experts to rate the degree of membership of each risk factor u_i relative to each security level v_j , and calculate the membership vector $r_j=(r_{i1}, r_{i2}, \dots, r_{i5})$ for each factor. The membership vectors of all factors form a fuzzy relationship matrix $R=(r_{ij})_{m \times 5}$, where r_{ij} represents the membership degree of factor u_i to level v_j , and satisfies $\sum_j r_{ij} = 1$.

(3) Fuzzy synthesis operation

Synthesize the weight vector W obtained by AHP with the fuzzy relationship matrix R to obtain the comprehensive evaluation vector B :

$$B = W \circ R = (w_1, w_2, \dots, w_m) \circ \begin{pmatrix} r_{11} & r_{12} & \dots & r_{15} \\ r_{21} & r_{22} & \dots & r_{25} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{m5} \end{pmatrix} \quad (4)$$

Among them, " $\circ$ " is a fuzzy synthesis operator. In this study, a weighted average operator $M(\cdot, \oplus)$ is used, that is, $b_j = \sum_i (w_i r_{ij})$. This operator can fully utilize the weight information of all factors and is suitable for safety comprehensive evaluation scenarios.

(4) Determine the security level

According to the principle of maximum membership degree [7], the comment level corresponding to the component with the highest value in the comprehensive evaluation vector B is taken as the final safety level of the repetitive diving activity:

$$Level = v_k, \text{ Among which } k = \arg \max_{1 \leq j \leq 5} b_j \quad (5)$$

2.4. Data Collection and Quality Control

Both AHP judgment matrix questionnaire and fuzzy evaluation questionnaire adopt standardized format. Double independent entry, cross-checking. The weight calculation and consistency check of AHP adopt Yaahp, and the fuzzy comprehensive evaluation operation is realized by Python programming.

3. Result Analysis

3.1. Identification of Risk Factors and Construction of Index System

Through literature analysis and two rounds of Delphi expert consultation, the safety evaluation index system of

repetitive diving is finally determined. A total of 18 questionnaires were distributed in the first round of consultation, and 16 valid questionnaires were recovered, with a recovery rate of 88.9%; Sixteen questionnaires were distributed in the second round of consultation, and 15 valid questionnaires were recovered, with a recovery rate of 93.8%. The Kendall coordination coefficient of expert opinions

increased from 0.372 ($\chi^2=68.54$, $p<0.01$) in the first round to 0.561 ($\chi^2=97.23$, $p<0.001$) in the second round, indicating that expert opinions tend to be consistent after two rounds of consultation. Finally, the repetitive diving safety evaluation index system includes 4 index levels and 16 index levels, as shown in Table 1.

Table 1. Repetitive diving safety evaluation index system

Target layer	Criterion layer	Indicator level	Indicator description
Repetitive diving safety review(A)	Physiological factors (B ₁)	Age (C ₁₁)	The older the age, the lower the nitrogen removal efficiency
		Body Mass Index (C ₁₂)	BMI ≥ 30 is considered high-risk
		Fatigue level (C ₁₃)	Subjective fatigue sensation before diving
		Previous history of decompression(C ₁₄)	Individuals with a history of DCS have an increased risk of recurrence
	Diving operation factors(B ₂)	Maximum diving depth(C ₂₁)	Deep increase significantly increases DCS risk
		Underwater residence time (C ₂₂)	The longer the time, the greater the nitrogen load
		Rising rate(C ₂₃)	Rapid rise increases the risk of bubble formation
		Diving times(C ₂₄)	Daily re diving frequency, each re diving reduces DCS risk by about 6%
	Interval and cumulative factors(B ₃)	Water surface interval time (C ₃₁)	Increasing by 1 hour each time reduces DCS risk by approximately 4%
		Residual nitrogen from previous diving (C ₃₂)	Residual nitrogen load in the body
		Multi-day cumulative diving (C ₃₃)	Diving continuously for multiple days, DCS risk increases after 4-5 days
		Post-diving exercise (C ₃₄)	Intense exercise after diving increases risk
	Environmental and equipment factors(B ₄)	Water temperature(C ₄₁)	Cold water environment increases DCS risk
		State of the sea(C ₄₂)	Adverse sea conditions such as wind, waves, and currents
		Equipment status(C ₄₃)	Equipment malfunction or improper use
		Dehydrated state(C ₄₄)	Dehydration increases DCS risk

3.2. AHP Weight Calculation Result

According to the judgment matrix data of the second round of consultation by 15 experts, the index weights of each level are calculated and the consistency test is carried out one by

one. The CR values of all judgment matrices are less than 0.10, and they pass the consistency test. The weight results of criteria layer and index layer are shown in Table 2.

Table 2. Weight of safety evaluation indicators for regenerative diving

Criterion layer	Weight	Indicator level	Combined weight
Physiological factors (B ₁)	0.231	Age (C ₁₁)	0.052
		Body Mass Index (C ₁₂)	0.048
		Fatigue level (C ₁₃)	0.061
		Previous history of decompression(C ₁₄)	0.070
Diving operation factors(B ₂)	0.318	Maximum diving depth(C ₂₁)	0.102
		Underwater residence time (C ₂₂)	0.085
		Rising rate(C ₂₃)	0.073
		Diving times(C ₂₄)	0.058
Interval and cumulative factors(B ₃)	0.274	Water surface interval time (C ₃₁)	0.096
		Residual nitrogen from previous diving (C ₃₂)	0.067
		Multi-day cumulative diving (C ₃₃)	0.055
		Post-diving exercise (C ₃₄)	0.056
Environmental and equipment factors(B ₄)	0.177	Water temperature(C ₄₁)	0.049
		State of the sea(C ₄₂)	0.041
		Equipment status(C ₄₃)	0.052
		Dehydrated state(C ₄₄)	0.035

In the criterion layer, diving operation factor (B₂, weight 0.318) has the greatest influence on the safety of repetitive diving, followed by interval and accumulation factor (B₃, weight 0.274) and physiological state factor (B₁, weight 0.231), while environment and equipment factor (B₄, weight 0.177) have relatively little influence. This weight distribution suggests that the focus of repetitive diving risk

management should give priority to diving operation specifications and water surface interval control.

Among all 16 indicator layer factors, the top five in terms of combined weights are maximum diving depth (C₂₁, 0.102), underwater dwell time (C₂₂, 0.085), water surface interval time (C₃₁, 0.096), ascent rate (C₂₃, 0.073), and past DCS history (C₁₄, 0.070). This ranking is consistent with the

conclusions of existing epidemiological studies. Previous studies have shown that every time the number of repetitive divisions increases [8], the risk of DCS will be reduced by about 6% (OR=0.94), while every hour of water surface interval will reduce the risk of DCS by about 4% (OR=0.96).

The weight results of this study further verify the relative importance ranking of the above variables from the perspective of multi-factor comprehensive evaluation. The factors of diving operation are prominent in the two indexes of "maximum depth" and "underwater time", while the factors of interval and accumulation are concentrated in the "water surface interval".

3.3. FCE and Safety Classification

According to the weight results of AHP, FCE is further used to evaluate the safety level of repetitive diving. Let the comment set $V=\{v_1, v_2, v_3, v_4, v_5\}=\{\text{low risk, low risk, medium risk, high risk, high risk}\}$. Taking a typical repetitive diving scenario as an example for comprehensive evaluation, a 45 year old male recreational diver with a BMI of 28 and no history of DCS plans to dive for the second time of the day.

The previous dive had a maximum depth of 28 meters, stayed underwater for 35 minutes, and had a water surface interval of 2.5 hours. The proposed depth for this dive is 25 meters, with a planned stay of 30 minutes. The seawater temperature is 22 °C, and the diver feels mild fatigue.

After 15 experts evaluated the membership scores of various indicators in the scene, a fuzzy relationship matrix was obtained through statistics, which was combined with weight vectors to obtain a comprehensive evaluation vector:

$$B=W \circ R=(0.152, 0.287, 0.334, 0.181, 0.046)$$

According to the principle of maximum membership degree, the safety level of this repetitive diving scenario is rated as "medium risk" ($b_3=0.334$ is the maximum value), indicating that there are certain safety hazards in this repetitive diving activity. It is recommended to take targeted risk control measures.

To further verify the effectiveness of the grading evaluation model, six representative repetitive diving scenarios were selected for safety level assessment, and the results are shown in Table 3.

Table 3. Safety rating results of typical repetitive diving scenarios

Scene number	Scene description	Comprehensive evaluation vector	security level
S1	Young diver (28 years old), in good physical condition, with a 6-meter interval between first and second dives, at a depth of 20 meters	(0.342, 0.356, 0.218, 0.072, 0.012)	Lower risk
S2	Middle aged diver (45 years old), mild fatigue, repeated diving every 3 hours, depth 25 meters	(0.152, 0.287, 0.334, 0.181, 0.046)	Medium risk
S3	Senior diver (58 years old), BMI 31, Repetitive diving with an interval of 1.5 hours and a depth of 30 meters	(0.045, 0.118, 0.263, 0.352, 0.222)	Higher risk
S4	Healthy youth, diving for the 4th consecutive day, diving for the 3rd day, with an interval of 2 hours	(0.082, 0.165, 0.291, 0.308, 0.154)	Higher risk
S5	Previous DCS history, repetitive diving depth of 35 meters, with a relatively fast rate of increase	(0.028, 0.076, 0.185, 0.297, 0.414)	High risk
S6	Healthy middle-aged, fully rested, repeated diving at 12 hour intervals, depth of 18 meters, using high oxygen	(0.418, 0.372, 0.152, 0.048, 0.010)	Low Risk

As can be seen from Table 3, the rating results of the model are basically consistent with the intuitive risk judgment of each scenario. Water surface interval and maximum diving depth are key variables to distinguish low-risk and high-risk scenarios. S6 (interval of 12 h, depth of 18 m) is rated as low risk, while S3 (interval of 1.5 h, depth of 30 m) is rated as high risk, which is consistent with the statement in MSD manual that "heavy repetitive diving water is more likely to lead to DCS". Multi-day cumulative effect is also reflected in S4. After continuous multi-day diving, even if the single-day diving parameters are not extreme, the cumulative risk will still push the safety level to a higher risk.

3.4. Modelling Verification

To verify the effectiveness of the constructed AHP-FCE evaluation model, 35 real recreational diving repetitive diving cases were selected, which were sourced from the diving accident reporting system and diving club log records. The safety level was automatically evaluated by the model and independently evaluated by three senior diving experts (two diving medical physicians and one diving coach). The agreement rate between the model evaluation and expert evaluation was calculated based on the majority expert opinion as the gold standard. The results are shown in Table 4.

Table 4. Consistency rate between model evaluation and expert evaluation

Expert evaluation level	Number of cases	Number of consistent cases of model evaluation	Consistency rate (%)
Low Risk	8	7	87.5
Lower risk	7	6	85.7
Medium risk	9	7	77.8
Higher risk	6	5	83.3
High risk	5	4	80.0
Total	35	29	82.9

The overall agreement rate of the model is 82.9%(29/35), which is higher than the preset acceptable threshold of 80%. Among them, the coincidence rates of low-risk scenarios and low-risk scenarios are higher, 87.5% and 85.7% respectively, and the coincidence rate of medium-risk scenarios is relatively low. The analysis may be due to the vague boundary conditions of medium-risk scenarios and the relatively large differences in judgment among experts. Generally speaking,

the evaluation results of the model are in good agreement with the expert's experience judgment, which shows that the AHP-FCE repetitive diving safety classification evaluation model has good practicability and reliability.

4. Conclusion

In view of the lack of special risk assessment tools for

recreational divers in the repetitive diving scene, this study systematically constructed a repetitive diving safety classification evaluation model through literature analysis, two rounds of Delphi expert consultation and the combination of AHP and FCE. The results show that the AHP-FCE regenerative diving safety grading evaluation model constructed in this study has both theoretical rationality and practical reliability. It can provide quantitative scientific reference for the course design of diving training institutions, self risk assessment of regenerative divers, and the formulation of industry safety management standards. It has positive practical significance for reducing the incidence of regenerative diving accidents and promoting the healthy and sustainable development of recreational diving sports.

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