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IJCMB
International Journal of Clinical Medicine and Bioengineering

ISSN 2737-534X
Volume 5, Issue 4
https://ijcmb.iikii.com.sg
International Journal of Clinical Medicine and Bioengineering

Article

Data-Driven Screening Model for Tinnitus Risk Level Classification System Based on Clinical Information and Associated Risk Factors

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Received: Apr 15, 2025; **Revised:** May 29, 2025; **Accepted:** May 29, 2025; **Published:** Dec 30, 2025

Abstract: Tinnitus affects approximately 15% of the global population, with prevalence rising to 25% among adults over the age of 60. Its complex and multifactorial cause, including hearing loss, psychological stress, mental health disorders, and neurological conditions, makes diagnosis and management particularly challenging. The severity of tinnitus varies widely and often disrupts daily functioning, yet the absence of a standardized screening method for assessing tinnitus risk contributes to delays in diagnosis and inefficient use of healthcare resources. This study aims to develop and validate a tinnitus risk screening tool tailored to the Taiwanese population, based on easily accessible medical information such as hypertension, diabetes, obesity, and lifestyle habits (e.g., smoking, alcohol use). A two-stage framework was implemented, combining rule-based analysis with a quantitative risk scoring system to classify individuals into low-, moderate-, and high-risk categories. Validation against expert clinical judgment achieved 88.2% accuracy in identifying high-risk tinnitus cases. By leveraging routine clinical data, this tool facilitates prompt care for individuals with serious tinnitus, particularly in primary care or resource-limited settings lacking specialized diagnostic tools. The proposed screening model offers practical value for healthcare providers, patients, and caregivers, enabling timely intervention and reducing the medical, emotional, and economic burdens associated with tinnitus.

Keywords: Tinnitus, Risk classification, Screening model, Taiwanese population, Risk stratification, Early intervention

1. Introduction

Tinnitus refers to hearing sounds in the ears or head with no external sound present, influencing around 10–15% of adults worldwide [1]. Among them, 1–5% experience severe symptoms, and prevalence increases with age, reaching up to 25% among individuals aged 60 to 69 years [2]. With increasing longevity in life expectancy, tinnitus cases are likely to rise, presenting a major public health concern [3]. Despite the numerous research efforts to understand the mechanisms underlying tinnitus, no singular etiology has emerged [4]. Based on sound perception, tinnitus can be classified into pulsatile and non-pulsatile tinnitus. For pulsatile, where the sound is rhythmic and synchronized with the patient's heartbeat and sometimes can be heard by the examiners. It is often caused by vascular abnormalities, muscle contractions, or middle ear conditions. In some cases, surgical intervention may be necessary [5]. Non-pulsatile tinnitus is more common than pulsatile tinnitus, where only the patient can hear ringing, buzzing, hissing, or clicking sounds in their ear. It is usually linked to auditory system disorders, including age-related hearing loss, nerve damage or noise exposure [6]. The tinnitus can happen in a one-sided ear (unilateral tinnitus) or in both ears (bilateral tinnitus).

Tinnitus not only causes auditory disturbances but also significantly affects daily life, often leading to sleep problems, anxiety, depression, and cognitive difficulties [7]. Lin *et al.* found that patients with tinnitus had a significantly higher risk of developing anxiety disorders compared to individuals without tinnitus [8]. For many individuals, tinnitus results in chronic distress, reducing overall quality of life and requiring long-term therapy and frequent medical follow-ups. Despite the availability of various treatment options—such as sound therapy, cognitive behavioral therapy (CBT), medications, and neuromodulation techniques—there is no official solution [9]. Treatment effectiveness varies widely between individuals, making it difficult to predict the most appropriate intervention for each patient [10,11]. Consequently, many tinnitus patients have to try multiple treatments, consult different healthcare providers, and incur substantial medical expenses without secured relief [12]. A study conducted in the Netherlands and Germany estimated the average annual healthcare expenditure related to tinnitus to be approximately 1,544 EUR per patient, equivalent to about 1,670 USD [3]. In comparison, studies in the U.S. and the U.K. reported average annual costs of around 663

USD and 1,762 British pounds, for clinical visits related to tinnitus [13]. Furthermore, tinnitus-related work inefficiency was estimated at 15.41 lost days, or 123 hours per patient annually, leading to productivity loss of 3,702 EUR, around 4000 USD [14]. Altogether, the total estimated cost per patient due to tinnitus is around 5,744 USD. In a study of 597 volunteers, Chang *et al.* reported a 32.0% prevalence of persistent and chronic tinnitus [15]. Despite its clear global burden, no study has investigated the economic impact of tinnitus in Taiwan to date. However, considering the international data, it is likely that tinnitus poses significant socioeconomic challenges in Taiwan as well.

Tinnitus severity is most commonly assessed using subjective questionnaires, such as the Tinnitus Handicap Inventory (THI), Tinnitus Activity Questionnaire (TAQ), Tinnitus Functional Index (TFI), and Visual Analog Scale (VAS) [16]−[18]. These tools evaluate how tinnitus affects a patient's daily life and are widely used for screening, treatment monitoring, and treatment outcome evaluation. These assessments could enhance personalized treatment planning, improve monitoring, and advance research methodologies in tinnitus studies. Over time, various screening methods have been introduced, each serving specific clinical or research purposes. For example, some approaches classify tinnitus based on duration, distinguishing between acute and chronic cases, while others are based on etiology or symptom characteristics. Henry *et al.* proposed a four-item algorithmic tinnitus screener that assessed tinnitus's presence and temporal nature [19]. While useful, this tool did not distinguish between temporary and chronic tinnitus. To address this limitation, Thielman *et al.* evaluated the short-term test-retest reliability of an expanded six-item tinnitus screener, to determine the stability of tinnitus classification over time and whether reliability varies by age, sex, military status, and hearing loss [20]. It classified tinnitus into five categories: No tinnitus, temporary, occasional, intermittent, and constant. In their classification system, individuals reporting constant or intermittent tinnitus were considered positive for tinnitus, while all others were classified as not harmful. Although these tools are valuable, they rely heavily on patients' personal feeling, which can lead to variability in responses. This subjectivity introduces inconsistencies that may reduce the accuracy of clinical decision-making and impact the reliability of research outcomes.

Effective tinnitus management requires a reliable screening method for risk-level classification. By categorizing patients based on the severity of symptoms and associated risk factors, clinicians are able to create individualized care plans for individual patient needs., ensuring that each individual receives the most appropriate care. Risk classification also plays a vital role in optimizing healthcare resources, allowing high-risk patients to be prioritized for specialized interventions. In this study, we developed a structured and standardized tinnitus risk classification model to support tinnitus patients with severe symptoms that need prompt intervention. The model integrates rule-based logic with a data-driven risk scoring system based on clinically validated risk factors such as hearing impairment, sleep disturbances, stress, smoking, and other health problems such as obesity and hypertension. We aim to enhance classification for clinical decision-making support, helping professionals recommend suitable treatments. The model promotes early detection of individuals with severe symptoms, enables personalized treatment, and improves resource allocation. Early identification of tinnitus risks increases awareness of its impact and ensures that high-risk individuals receive timely support and care.

2. Materials and Methods

2.1. Data Source

We used the electronic medical record (EMR) database of National Cheng Kung University Hospital (NCKUH) to investigate the prevalence, demographic distribution, and risk factors of tinnitus in the Taiwanese population. The study received ethical certificate from the Institutional Review Board (IRB No. BR-111-364). Adult patients were included if they had at least two medical encounters—such as outpatient visits, emergency department visits, or hospitalizations—with the Departments of Otolaryngology, Neurology, Family Medicine, or Neurosurgery between January 1, 2013, and December 31, 2022. Tinnitus cases were identified using diagnostic codes from the International Classification of Diseases (ICD), specifically ICD-9-CM code 388 and ICD-10-CM code H93. A total of 258 participants were included in the study, consisting of individuals diagnosed with tinnitus and those without tinnitus (serving as the control group). Table 1 presents the demographic characteristics of the study population.

Table 1. Detailed information for participants who joined in the experiment.

Inclusion criteria	
Period	January 1, 2013, and December 31, 2022
Diagnostic code	ICD-9-CM code 388 ICD-10-CM code H93

Healthcare encounters	Departments of Otolaryngology, Neurology, Family Medicine, or Neurosurgery
Number of EMRs	258 records
Exclusion criteria	
Diagnosis of Otitis media or middle ear related disorders	ICD-9-CM code 381, 382 ICD-10-CM code H65, H66, H74

2.2. Risk Factors Identification

While previous research has identified commonly associated risk factors for tinnitus, such as military service and tinnitus status, this study carried out an expanded cross-sectional approach [21]−[24]. We incorporated additional variables, including chronic diseases (e.g., diabetes, hypertension, and obesity) and lifestyle habits (e.g., smoking and alcohol consumption), based on established literature. These variables are detailed in Table 2. The goal of this analysis is to define tinnitus-specific risk factors within the Taiwanese population and to statistically evaluate their influence on tinnitus prevalence. Clinical experts conducted a thorough review of the EMRs for each selected participant, examining medical history, imaging reports, laboratory results, and medication records. Relevant risk factors and patient characteristics were extracted and compiled into a de-identified dataset for subsequent statistical analysis and risk assessment, independently verified by physicians.

Table 2. Risk factors characteristics and description.

Variable	Characteristics and Definitions
Hypertension (HTN)	Diagnosis HTN or HTN medication prescription
Hearing impairment (HI)	HI records or pure tone audiometry (PTA) above 25 dB
Diabetes mellitus (DM)	Diagnosed DM or anti-DM medication prescription
Dyslipidemia	Diagnosed dyslipidemia or either triglyceride (TG) $\geq$ 200 mg/dl or LDL-cholesterol $\geq$ 130 mg/dl
Obesity	Body mass index (BMI) $\geq$ 27 or weight length (male $\geq$ 90 cm, female $\geq$ 80 cm)
Sleeping disorders	Diagnosed insomnia or poor sleeping quality complaint records
Smoking	Cigarettes habit records
Alcoholism	Alcohol consumption records

Firstly, we conducted statistical tests to identify significant differences between the tinnitus and control groups, serving as the basis for considering relevant factors in the development of a tinnitus risk prediction model. Given the wide range of potential risk factors, we aimed to identify the most prevalent factors in the tinnitus group, that calculation shown in Table 3. Hearing impairment was observed in 61.2% of tinnitus patients compared to 2.3% of controls, while sleep disorders were reported in 32.6% of the tinnitus group versus 4.7% of the control group. These findings indicate a strong association between these conditions and tinnitus. In contrast, other factors—hypertension, diabetes mellitus, dyslipidemia, obesity, smoking, and alcoholism—did not show statistically significant differences between the two groups.

Table 3. Percentage of risk factors associated with the control group and the tinnitus group.

Risk factors (N=258)	Control, N=129	Tinnitus, N=129
Hypertension (HTN)		
No	85 (65.9%)	98 (76%)
Yes	44 (34.1%)	31 (24%)
Hearing impairment (HI)		
No	126 (97.7 %)	50 (38.8 %)
Yes	3 (2.3%)	79 (61.2%)
Diabetes mellitus (DM)		
No	102 (79.1%)	110 (85.3%)
Yes	27 (20.9%)	19 (14.7%)
Dyslipidemia		
No	81 (62.8%)	87 (67.4%)

Yes	48 (37.2%)	42 (32.6%)
Obesity		
No	111 (86%)	119 (92.2%)
Yes	18 (14%)	10 (7.8%)
Sleeping disorders		
No	123 (95.3%)	87 (67.4%)
Yes	6 (4.7%)	42 (32.6%)
Smoking		
No	113 (87.6%)	115 (89.1%)
Yes	16 (12.4%)	14 (10.9%)
Alcoholism		
No	120 (93%)	121 (93.8%)
Yes	9 (7%)	8 (6.2 %)

2.3. Mutiple Regression Methodology

Multiple regression analyses were conducted to evaluate the strength of association of potential risk factors with tinnitus occurrence. For each factor, the odds ratio (OR), a key output of logistic regression with a 95% confidence interval (CI), was calculated to quantify the strength of association with tinnitus. This regression method is particularly suitable for binary outcomes, such as the presence or absence of tinnitus, and transforms a linear combination of independent variables into a probability value ranging from 0 to 1. Statistically significant factors ($p < 0.05$) were retained for inclusion in the rule-based classification and scoring system. All statistical analyses were performed using R (version 4.2.2), applying a two-tailed hypothesis testing approach to ensure the reliability of the results.

The OR is widely used in medical research to evaluate the association between an exposure (e.g., a risk factor) and an outcome (e.g., tinnitus) [25]. The OR calculation process, illustrated in Equation (1), is based on a 2x2 contingency table (Table 4). An OR of 1 indicates no association, suggesting the risk factor has no effect on the developing tinnitus. An OR greater than 1 suggests an increased possibility, meaning the risk factor contributes to a higher chance of tinnitus. Conversely, an OR less than 1 implies a decreased probability, indicating the risk factor may not be the common reason leading to the development of tinnitus.

Table 4. Formula for odds ratio definition.

Inclusion criteria	Tinnitus (T+)	Non-tinnitus (T-)
Risk factor (R+)	A	B
No risk factor (R-)	C	D

$$OR = \frac{Odds\ of\ R^+ + inT^+}{Odds\ of\ R^- + inT^+} = \frac{A/B}{C/D} \quad (1)$$

Table 5 presents the results of the multiple logistic regression model analysis on risk factors associated with tinnitus, comparing the effects of various risk factors on the odds of developing tinnitus. The result, presented as ORs with corresponding 95% CI for the identified risk factors. The analysis revealed that most risk factors, such as diabetes mellitus, hypertension, obesity, and personal habits, did not exhibit a significant association with tinnitus ($p > 0.05$). In contrast, sleep disorder (OR = 3.8, 95% CI: 1.58 - 9.79, $p < 0.05$) was significantly associated with an increased risk of tinnitus, as indicated by OR values greater than 1.

Table 5. Multiple logistic regression analysis of factors associated with tinnitus.

Term	Estimated OR	Standard error	Statistic	p-value	CI-low	CI-high
Hypertension (HTN)	1.12	0.55	0.2	0.84	0.38	3.33
Hearing impairment (HI)	1.25	0.41	0.54	0.59	0.56	2.80
Diabetes mellitus (DM)	0.78	0.59	-0.41	0.68	0.25	2.54
Dyslipidemia	0.75	0.48	-0.59	0.56	0.29	1.93
Obesity	2.73	0.76	1.32	0.19	0.66	14.50
Sleeping disorders	3.80	0.46	2.89	0.00	1.58	9.79

Smoking	1.52	0.72	0.58	0.56	0.37	6.82
Alcoholism	2.90	1.20	0.89	0.38	0.33	61.87

2.4. Rule-based Analysis and Risk Scoring System

In this study, we applied a two-step approach for tinnitus risk-level classification, combining both rule-based analysis and a statistical risk-scoring method. In the first stage, individuals were evaluated using predefined high-risk criteria derived from established literature to directly identify those at elevated risk. For individuals who did not meet these initial criteria, a second-stage assessment was performed using a risk-scoring system, based on the statistical associations between various risk factors and tinnitus. This integrated strategy enabled us to classify participants into low-, medium-, and high-risk groups, providing a more comprehensive and data-driven risk assessment. The full methodology, including specific criteria and analytical processes, is detailed in the following sections. The structure of the proposed screening approach is illustrated in Figure 1.

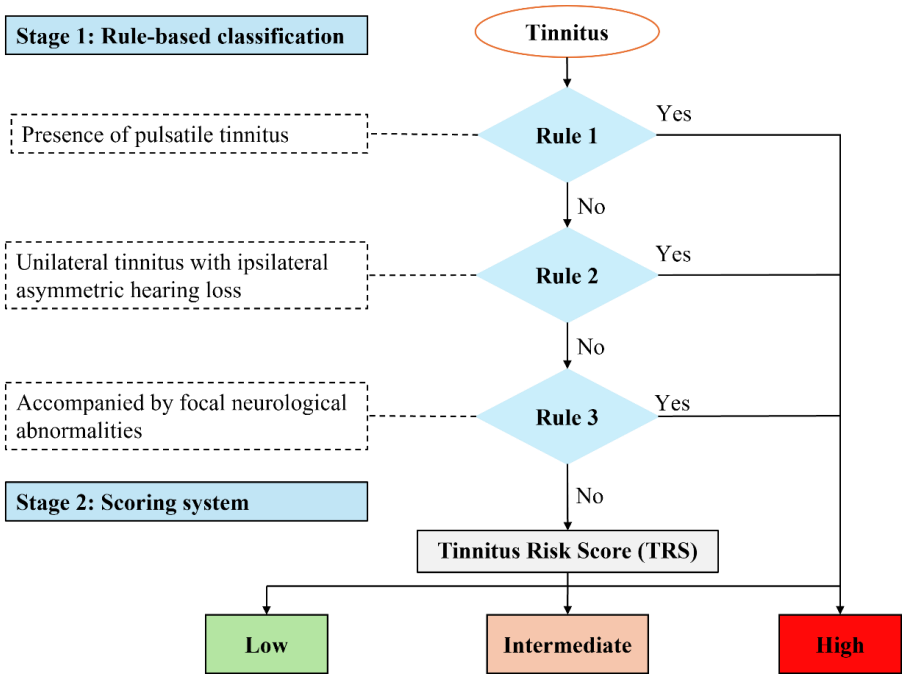

Fig. 1. Two-stage tinnitus risk factor classification structure, including rule-based and scoring system.

2.4.1. Rule-based Analysis

Building on previous research that has identified several risk factors closely linked to specific types and characteristics of tinnitus, this study introduces a structured screening mechanism aimed at identifying high-risk tinnitus cases from medical records. The mechanism is based on the following predefined rules:

Rule 1: Presence of pulsatile tinnitus

Rule 2: Unilateral tinnitus accompanied by ipsilateral asymmetric hearing loss

Rule 3: Tinnitus associated with focal neurological abnormalities

A sequential stratification process was conducted, starting from Rule 1 and moving through to Rule 3. Any individual meeting at least one of these criteria was directly classified as high-risk. For individuals who did not meet any of these criteria, a further risk-scoring assessment was applied to evaluate the risk level of tinnitus. This approach ensures an assessment of potential high-risk cases while enabling an efficient risk evaluation process for lower risk levels.

2.4.2. Tinnitus Risk Score (TRS) System

Based on the OR computations results presented in Table 5, which identified potential risk factors and their associations with tinnitus, we developed a TRS to classify individuals into high-, intermediate-, and low-risk groups. Each risk factor was assigned a score based on its corresponding OR for high-risk tinnitus. To standardize the scoring process, we calculated the natural logarithm of each OR (*ln* OR) and selected the value closest to zero as the reference point. Risk factors with negative *ln* OR values were

excluded to ensure the scoring system only reflected contributing risk factors of tinnitus. Among the positively associated variables, obesity, which had an *ln* OR closest to 1, was selected as the reference point. Variables with negative associations (OR < 1) were assigned a score of 0, indicating a minimal or no contribution to tinnitus risk. Scores were assigned for variables with positive associations based on their relative strength compared to the reference point. For example, obesity, sleep disorders, and alcohol abuse were each assigned a score of 2, while hypertension, hearing impairment, and smoking received a score of 1. The final score for each factor was defined by the integer of the OR value as shown in Table 6.

Table 6. Tinnitus risk scoring system establishment.

Factors	OR	*ln* OR	Scoring
Hypertension (HTN)	1.12	0.113	1
Hearing impairment (HI)	1.25	0.223	1
Diabetes mellitus (DM)	0.78	-0.248	0
Dyslipidemia	0.75	-0.288	0
Obesity	2.73	**1.004**	2
Sleeping disorders	3.80	1.335	3
Smoking	1.52	0.419	1
Alcoholism	2.90	1.065	2

Each participant's TRS was calculated by summing the scores of all contributing risk factors, resulting in a total score out of ten. Based on this total, risk categorization was established as follows: Scores ≥ 5 indicated high risk, scores between 2 and 5 signified moderate risk, and scores < 2 represented low risk. The risk classification thresholds for categorizing individuals into low-, intermediate-, and high-risk levels were determined through validation with clinical data to ensure the model's accuracy and reliability, as presented in Table 7. The threshold was set at 5 out of 10 total points based on the testing of various cutoff values. This value, representing approximately half of the maximum score, was chosen to optimize classification performance while minimizing the missing potential high-risk cases. It most closely matched the consensus high-risk group identified by these experts.

Table 7. TRS detailed categories and risk levels classification based on scores.

TRS items	Features	Weighted score
Hypertension (HTN)	Diagnosed HTN or HTN medication prescription	1
Hearing impairment (HI)	HI records or PTA above 25 dB	1
Obesity	BMI ≥ 27 or weight length (male ≥ 90 cm, female ≥ 80 cm)	2
Sleeping disorders	Diagnosed insomnia or poor sleeping quality complaint records	3
Smoking	Cigarettes habit records	1
Alcoholism	Alcohol consumption records	2
	Total	**10**
Categories		
Category I: High risk	TRS ≥ 5	
Category II: Intermediate risk	TRS <5 and ≥ 2	
Category III: Low risk	TRS < 2	

3. Model Validation and Results

To validate the accuracy and clinical relevance of the proposed tinnitus risk classification model, a population-based pilot study was conducted using 129 EMR data from National Cheng Kung University Hospital (NCKUH). Based on predefined selection criteria and resource limitations, the study included 129 individuals diagnosed with tinnitus to investigate the prevalence and impact of potential tinnitus risk factors within the Taiwanese population. Model development involved a two-step approach integrating rule-based classification and statistical modeling. To validate the model, its risk predictions were compared against clinical assessments provided by medical experts. All personal identifiers were removed from the dataset to maintain patient privacy and confidentiality.

The de-identified data were independently reviewed by two physicians (a neurologist and an otolaryngologist), who each assigned a tinnitus risk level to the participants based on clinical judgment. In cases of disagreement, a third physician was consulted, and the final decision was made through majority voting. The expert agreement served as the clinical reference standard to assess the concordance between the model's predictions and clinical evaluations. The validation process ensured that the model output was aligned with established clinical reasoning and supported its potential application in the early identification and management of tinnitus risk. The full experimental workflow is illustrated in Figure 2.

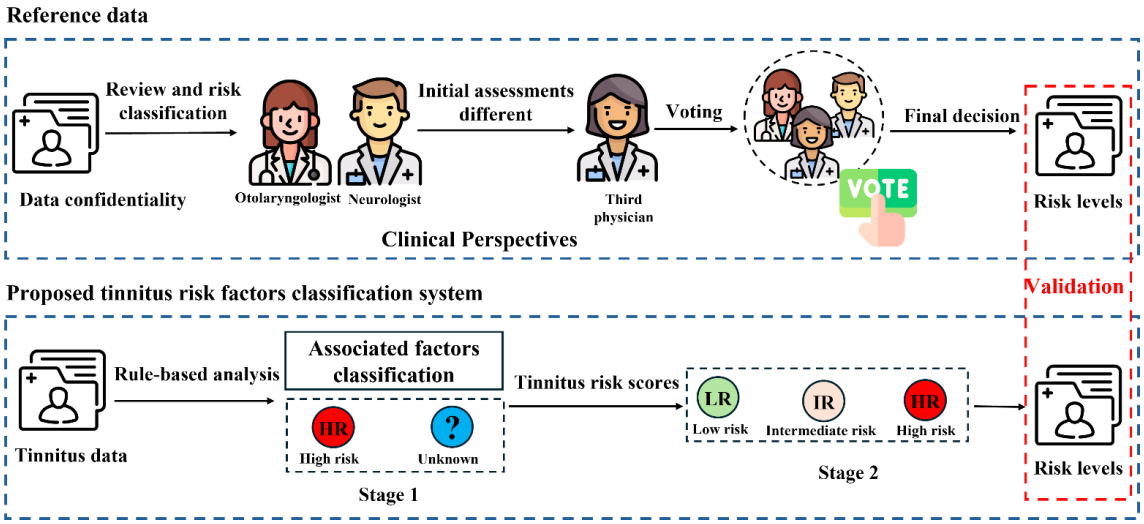

Fig. 2. The experimental process for a clinical data-driven approach.

Among the 129 tinnitus patients identified based on the diagnostic codes described above, the expert panel, comprising three physicians, classified 34 patients as high-risk, 45 as moderate-risk, and 50 as low-risk based on their final diagnosis. To evaluate the accuracy of the proposed risk assessment model compared to clinical judgment, the same patient cohort was classified using the developed rule-based stratification and scoring system. When compared against expert clinical judgment, the model correctly classified 30 patients as high-risk, 27 as moderate-risk, and 31 as low-risk. As shown in Table 8, this approach effectively classified individuals who have a high-risk level of tinnitus. The model performed particularly well in identifying high-risk cases, achieving an accuracy of 88.2% by correctly classifying 30 out of 34 individuals. However, its specificity was lower when distinguishing between low- and intermediate-risk groups, with precision rates of approximately 62% and 60%, respectively. These results indicate that while the screening method is highly effective for detecting high-risk tinnitus patients, additional refinement is needed to improve accuracy in classifying individuals at lower risk levels.

Table 8. Validation results of tinnitus screening between proposed system and medical experts.

Levels of risk	Low	Moderate	High
Verification results (counts)	50	45	34
Correct classifications (counts)	31	27	30
Accuracy (%)	62%	60%	88.2%

4. Limitation

Despite promising results, this study has several limitations. First, the sample size was relatively small (n = 258), which may affect the findings for the Taiwanese population. Second, although risk factor classification was validated by expert clinicians, there is still an element of subjectivity in clinical judgment that could influence the labeling. Moreover, the manual review of EMR data was time-consuming and labor-intensive. However, our aim was not to replace these well-established diagnostic tools (direct methods such as Self-Report Questionnaires, Psychoacoustic Measurements, Clinical Global Impression (CGI), and Minimal Clinically Important Difference (MCID) [26]) but rather to create a preliminary, easily accessible risk stratification method based on routine medical records and lifestyle factors. This approach could serve as an early screening mechanism, especially in settings where specialized tinnitus assessments are not immediately available.

5. Discussion

Existing tinnitus screening criteria primarily focus on defining the chronicity or duration of tinnitus and using threshold scores from questionnaires to assess its impact on daily life and mental health. A key strength of the current diagnostic approach is its reliance on patients' subjective descriptions, which are evaluated by physicians to confirm a tinnitus diagnosis, which reduces the misclassification of non-tinnitus conditions. However, inherent limitations remain, particularly in achieving severity classification.

EEG-based classification has demonstrated high accuracy and is widely recognized as an objective method in tinnitus research [27]. However, its implementation requires specialized EEG equipment and highly trained personnel, which can limit its accessibility in routine clinical settings. In contrast, our study utilizes readily available medical data in Taiwan, such as common comorbidities (e.g., hypertension, diabetes, obesity) and lifestyle factors (e.g., smoking, alcohol use), which are easier and quicker to obtain during standard clinical visits. Despite relying on more accessible data, our two-stage risk assessment model, integrating a rule-based analysis with the TRS system model, successfully identified high-risk tinnitus patients with an accuracy of 88%, supporting its potential for early intervention and timely treatment in healthcare environments. However, classification performance for moderate- and low-risk groups was comparatively lower, with accuracies below 70%, highlighting a need for further refinement.

These findings indicate that even commonly recorded health data can contribute valuable insights in defining tinnitus severity. Although our approach did not include some tinnitus-specific clinical characteristics (e.g., pitch, loudness, duration), the integration of standard comorbidities and personal health behaviors offers a practical pathway for scalable risk stratification. Future versions of the model may benefit from incorporating more granular occupational (construction worker or military service) or detailed tinnitus symptom profiles to enhance precision across all risk levels.

6. Conclusions

We proposed the classification of tinnitus risk factors based on local demographics by identifying key risk factors specific to the Taiwanese population and clinical perspectives. The current model should be regarded as a supportive tool to identify individuals who may need further clinical evaluation. With an observed accuracy of 88% in identifying high-risk tinnitus cases, the model demonstrates potential as a screening tool for tinnitus diagnosis and management. For future work, we plan to validate our model on a larger, multi-center dataset encompassing a more diverse population to enhance its robustness and generalizability. Additionally, we aim to incorporate more advanced classification techniques, such as ensemble methods or neural networks, that are capable of modeling complex, nonlinear relationships among variables, thereby improving predictive performance and clinical utility. To expand the reach and utility of the proposed screening tool, we can integrate it into existing hospital information systems (HIS) or EMR or smartphone-based platforms; thus, healthcare systems can promote proactive tinnitus screening, especially in high-risk populations, and support early clinical intervention. Finally, our approach aims to reduce the global economic and healthcare burdens associated with tinnitus, leading to improved patient outcomes.

Author Contributions: N.-N.-H. Lam: Writing - Contributed to the initial and final manuscript, visualization, and editing; M.-J. Wu: Formal analysis, resources, validation, methodology; C.-L. Kuo: Methodology, formal analysis, data curation, investigation; Y.-C. Du: Supervision, methodology, conceptualization, resources, validation.

Funding: This research was not funded by any external sources.

Institutional Review Board Statement: The clinical trial was approved and conducted by the Institutional Review Board of National Cheng Kung University Hospital with IRB No. BR-111-364 for studies involving humans.

Informed Consent Statement: Informed consent in writing was obtained from the patients for the publication of this research.

Data Availability Statement: The corresponding author can provide the data of this study upon reasonable request.

Conflicts of Interest: The authors declare that there is no conflict of interest.

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