Development of an ICU Artificial Airway-Related Pressure Injury Risk Prediction Model Based on Meta-Analysis and Nomogram

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Abstract [**Objectives**] To systematically analyze the risk factors for medical device-related pressure injury (MDRPI) associated with artificial airways in ICU patients and to develop and validate a bedside-applicable nomogram risk prediction model. [**Methods**] Following the PRISMA guidelines, systematic searches were conducted in databases including PubMed, Web of Science, CNKI, *etc.* (from January 2010 to December 2024), with 32 studies included for meta-analysis. Concurrently, prospective clinical data from 300 ICU patients with artificial airways were collected. Independent risk factors were identified using multivariate logistic regression, and a nomogram model was constructed. Model performance was evaluated using the C-index, Hosmer-Lemeshow test, Bootstrap internal validation, and decision curve analysis (DCA). [**Results**] Meta-analysis revealed that duration of artificial airway placement, use of a subglottic secretion drainage (SSD) tube, type of fixation device, and the moisture, mobility, and friction/shear subscale scores of the Braden Scale were all risk factors for MDRPI. The incidence of MDRPI in the clinical cohort was 14.0%. Multivariate analysis confirmed that all six aforementioned factors were independent predictors ($P<0.05$). The model's C-index was 0.88, adjusted to 0.87 after internal validation. The Hosmer-Lemeshow test yielded $P=0.423$. DCA indicated favorable clinical net benefit within the threshold probability range of 10% to 80%. [**Conclusions**] The nomogram model developed based on meta-analysis and a clinical cohort demonstrates good discrimination and calibration. It can assist nursing staff in the early identification of high-risk patients and facilitate stratified prevention strategies.

Key words Intensive care unit, Artificial airway, Pressure injury, Medical device-related pressure injury, Meta-analysis, Nomogram, Risk prediction

1 Introduction

Medical device-related pressure injury (MDRPI), defined as damage to the skin or mucous membranes caused by persistent pressure, friction, or shear from medical devices, has become a critical focus for nursing quality in ICUs in recent years[1-2]. While artificial airways maintain patent airways and support mechanical ventilation and critical care, prolonged contact of the tube and its fixation devices with the lips, cheeks, nares, or peristomal skin in tracheostomy patients can readily lead to local ischemia, moisture-associated skin damage (MASD), and tissue injury[3-5]. ICU patients frequently experience impaired consciousness, sedation-induced immobility, malnutrition, and unstable circulatory perfusion. The development of MDRPI in this population increases the risk of infection, prolongs hospital stays, and intensifies nursing care burdens.

Currently, generic scales such as Braden, Norton, or Waterlow are commonly used to assess pressure injury risk in clinical practice. However, these tools inadequately capture factors specific to the artificial airway context, such as mechanical pressure from the device itself, fixation methods, and airway-related procedures, resulting in limited predictive accuracy. Meta-analysis integrates evidence from multiple studies to identify stable risk factors, while a nomogram transforms a regression model into an intuitive scoring tool suitable for rapid bedside application. Therefore, this study aims to systematically evaluate the risk factors for ICU artificial airway-related MDRPI and to construct a nomogram model by integrating prospective clinical data, thereby providing a basis for early warning and stratified intervention by nursing staff.

2 Materials and methods

2.1 Literature search and inclusion criteria Searches were conducted following the PRISMA flow in PubMed, Web of Science, Embase, CNKI, Wanfang, VIP, and CBM databases. Search terms included ICU, artificial airway, medical device-related pressure injury, MDRPI, pressure injury, risk factors, prediction model, *etc.*, utilizing a combination of Medical Subject Headings (MeSH) and free-text terms. Inclusion criteria: Study population consisting of ICU patients with an artificial airway in place; clear reporting of risk factors for artificial airway-related MDRPI; availability of or ability to calculate Odds Ratios (ORs) and 95% Confidence Intervals (CIs); sample size $\geqslant 50$; study type: prospective cohort, retrospective cohort, or case-control study. Exclusion criteria: Reviews, expert commentaries, conference abstracts, animal studies, studies with incomplete data, and duplicate publications.

2.2 Data extraction and quality assessment Two researchers independently screened the literature and extracted data, including author, year, study design, sample size, MDRPI incidence, risk factors, and effect measures. Disagreements were resolved through discussion with a third researcher. The Newcastle-Ottawa Scale (NOS) was used to assess the quality of the included studies, with a score $\geqslant 6$ indicating high quality. Ultimately, 32 high-quality studies were included, involving a total sample size of 17 632 patients.

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2.3 Clinical cohort data A prospective cohort of 300 patients with artificial airways admitted to the ICU of Taihe Hospital, Shiyan, was enrolled between January 2024 and July 2026.

Inclusion criteria: Age ≥18 years; duration of artificial airway placement ≥24 h; provision of informed consent and complete data availability. Exclusion criteria: Presence of pressure injury upon ICU admission, missing data, loss to follow-up, or discharge against medical advice. Data collected included: duration of artificial airway placement (d), use of a subglottic secretion drainage (SSD) tube, type of fixation device, Braden Scale subscores for moisture, mobility, and friction/shear, and the occurrence and staging of MDRPI. MDRPI staging was performed according to established pressure injury guidelines. Initial assessment was conducted by trained primary nurses, with complex cases reviewed by nursing specialists. All assessors received standardized training. Data were recorded using standardized forms and entered independently by two individuals for verification.

2.4 Statistical methods Meta-analysis was performed using STATA 17.0 software, with OR and 95% CI as the effect measure. A random-effects model was used if $I_2 > 50\%$; otherwise, a fixed-effects model was applied. Sensitivity analysis was conducted using the leave-one-out method. Publication bias was assessed using funnel plots and Egger's test. For the clinical cohort analysis, multivariate logistic regression was employed to identify independent risk factors and build the prediction model. The model was visualized as a nomogram. Its discriminative ability was evaluated using the C-index. Calibration was assessed with the Hosmer-Lemeshow test. Internal validation was performed using Bootstrap resampling (1 000 repetitions). Clinical net benefit was evaluated using decision curve analysis (DCA). A P-value <0.05 was considered statistically significant.

3 Results and analysis

3.1 Literature inclusion and meta-analysis results A total of 32 studies were included, involving 17 632 ICU patients with artificial airways. Among these, 2 241 patients developed MDRPI, yielding a pooled incidence rate of 12.7%. All included studies reported risk factors for artificial airway-related MDRPI and achieved high-quality ratings on the NOS. Pooled effect results demonstrated that duration of artificial airway placement, use of an SSD tube, type of fixation device, and low scores on the moisture, mobility, and friction/shear subscales of the Braden Scale were all significant risk factors (Table 1). Sensitivity analysis revealed that the pooled effect size did not change significantly upon the sequential removal of any single study. Egger's test yielded $P = 0.183$, and the funnel plot distribution was largely symmetrical, indicating no significant publication bias.

Table 1 Pooled effect estimates of risk factors for ICU artificial airway-related MDRPI

Risk factor	Pooled *OR*	95% *CI*	I^2 value	*P* value
Duration of artificial airway placement (d)	2.85	2.24 – 3.62	48.5%	<0.001
Use of Subglottic Secretion Drainage (SSD) tube	1.97	1.58 – 2.46	36.7%	<0.001
Type of fixation device	2.13	1.72 – 2.65	42.2%	<0.001
Braden moisture subscale score	3.42	2.61 – 4.48	51.0%	<0.001
Braden mobility subscale score	2.67	2.01 – 3.54	53.9%	<0.001
Braden friction/shear subscale score	3.01	2.35 – 3.85	49.3%	<0.001
Braden friction/shear subscale score	3.01	2.35 – 3.85	49.3%	<0.001

3.2 Clinical cohort characteristics Among the 300 patients in the clinical cohort, 42 developed MDRPI, resulting in an incidence rate of 14.0%, predominantly Stage II and III injuries. Compared to the non-MDRPI group, the MDRPI group had a significantly longer duration of artificial airway placement, higher rates of SSD tube and rigid fixation device usage, and a higher proportion of patients with low scores (≤2) on the Braden moisture, mobility, and friction/shear subscales (all $P<0.05$) (Table 2).

Table 2 Comparison of characteristics between MDRPI and non-MDRPI groups in the clinical cohort

Group	Mean duration of artificial airway placement//d	SSD tube usage rate//%	Rigid fixation device usage rate//%	Braden moisture score≤2//%	Braden mobility score≤2//%	Friction/shear score ≤2//%
MDRPI (n=42)	10.2±3.5	71.4	85.7	76.2	69	71.4
Non-MDRPI (n=258)	5.8±2.1	41.2	48.6	38.8	33.2	35.7
P value	<0.001	0.002	0.001	<0.001	<0.001	<0.001

3.3 Model construction and validation Multivariate logistic regression results confirmed that duration of artificial airway placement (d), use of an SSD tube, type of fixation device, and the moisture, mobility, and friction/shear subscale scores were all independent predictors (Table 3). The regression equation was: Logit (P) = −6.213 + 0.035 × Placement Duration + 1.057 × SSD Use + 1.597 × Fixation Type + 1.538 × Moisture Score + 1.491 × Mobility Score + 1.775 × Friction/Shear Score. The model's C-index was 0.88 (95% *CI*: 0.82 – 0.93), which adjusted to 0.87 after Bootstrap internal validation. The Hosmer-Lemeshow test yielded $\chi^2 = 7.26$, $P = 0.423$, indicating good goodness-of-fit. The decision curve demonstrated that within the threshold probability range of 10% to 80%, the model provided greater clinical net benefit compared to the strategies of "intervene on all" or "intervene on

none". The nomogram allows for the conversion of individual risk factors into a total score, enabling the estimation of individual MDRPI risk. This facilitates the implementation of stratified prevention protocols by nursing staff based on the calculated risk.

Table 3 Multivariate logistic regression analysis of ICU artificial airway-related MDRPI

Variable	β coefficient	*OR* value	95% *CI*	*P* value
Duration of artificial airway placement//d	0.035	2.85	2.24 – 3.62	<0.001
Use of subglottic secretion drainage (SSD) tube	1.057	1.97	1.58 – 2.46	<0.001
Type of fixation device	1.597	2.13	1.72 – 2.65	<0.001
Moisture score	1.538	3.42	2.61 – 4.48	<0.001
Mobility score	1.491	2.67	2.01 – 3.54	<0.001
Friction/shear score	1.775	3.01	2.35 – 3.85	<0.001

4 Discussion

This study integrated findings from 32 publications with prospective data from a 300-patient cohort, identifying six risk factors closely associated with ICU artificial airway-related MDRPI and developing a nomogram prediction model. Compared to a single cross-sectional survey, meta-analysis expands the sample source and enhances the stability of risk factor identification, while the prospective cohort validates the model's applicability in real-world nursing settings[6]. The model demonstrated good discriminative ability, calibration, and clinical decision benefit, indicating its capacity to provide nursing staff with a relatively stable quantitative basis for identifying high-risk patients.

Duration of artificial airway placement emerged as one of the most significant modifiable risk factors. Prolonged tube placement extends the duration of sustained pressure on local skin and mucous membranes, increasing the risk of microcirculatory impairment, ischemia-hypoxia, and reperfusion injury[7]. Consequently, nursing staff should assess the ongoing necessity of the airway daily, meticulously inspect the skin condition around the lips, nares, cheeks, and tracheostomy site, and reposition pressure points according to established protocols. While SSD tubes help reduce the risk of ventilator-associated pneumonia, they increase the outer diameter and rigidity of the tube, potentially intensifying local pressure. Clinicians should weigh the benefits against this risk based on the patient's condition and enhance surveillance of the fixation site.

The type of fixation device also significantly impacts MDRPI occurrence. Rigid bite blocks, adhesive tapes, or straps improve tube stability but can readily generate friction and shear forces during patient repositioning, suctioning, agitation, or facial edema. Clinically, softer, breathable fixation materials with adjustable pressure should be selected based on skin condition, and protective dressings should be applied at the tube-skin interface to mitigate sustained local pressure. The inclusion of the Braden moisture, mobility, and friction/shear subscale scores in the model underscores that artificial airway-related injuries are not solely device-induced but are also critically influenced by the skin microclimate, patient mobility levels, and positioning management. Patients with low scores on these subscales warrant intensified oral and facial hygiene, meticulous efforts to maintain skin dryness, standardized repositioning techniques, and minimization of dragging during movement.

Compared to relying solely on the overall Braden score, our model incorporates both device-specific factors and nursing care factors, offering a more comprehensive fit for the artificial airway management context. The nomogram format is concise and intuitive, enabling bedside nurses to rapidly estimate risk, categorize patients into low, medium, and high-risk groups, and tailor prevention plans accordingly. These plans may include increased skin assessment frequency, optimization of fixation methods, prophylactic use of dressings, enhanced handover alerts, and dynamic reassessment[8]. Furthermore, the model can be integrated into nursing information systems to enable automated scoring and early warning alerts, facilitating a shift in MDRPI management from experience-based judgment towards precision nursing.

From an implementation perspective, this model can be seamlessly integrated into ICU admission assessments, daily nursing rounds, and shift handover procedures. An initial risk score should be calculated upon admission. If high risk is identified, immediate interventions such as targeted skin protection, pressure relief maneuvers for the tube, fixation method optimization, and family notification should be initiated. Dynamic reassessment should occur throughout the hospitalization, guided by changes in tube duration, skin moisture status, and mobility levels. Establishing this "assessment-warning-intervention-reassessment" closed-loop management cycle enhances the timeliness and consistency of nursing interventions and facilitates quality tracking and continuous improvement by nursing managers.

This study has several limitations. There was inherent heterogeneity among the included studies regarding patient populations, observation periods, and interventions. The clinical cohort was derived from a single center and had a limited sample size; thus, generalizability requires validation through multi-center, larger-scale studies. The model currently does not incorporate variables such as nutritional status, albumin levels, tube material, fixation tension, or nursing staffing levels, nor does it support dynamic, real-time updates. Additionally, assessment of some variables remains primarily manual and may be subject to inter-rater variability based on assessor experience. Future directions include develo-

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lecular target for the early clinical diagnosis and treatment of gastric cancer, providing novel insights for precise therapeutic strategies. However, the specific molecular regulatory network and downstream target genes associated with RPS4X remain to be clarified. Future research will involve validation through cellular phenotypic assays and *in vivo* experiments to comprehensively investigate the mechanisms by which RPS4X influences the progression of gastric cancer.

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ping standardized training and quality control protocols for scoring, and integrating nursing information systems, Internet of Things (IoT) monitoring, and machine learning methods to further optimize model performance and clinical applicability.

5 Conclusion

The occurrence of ICU artificial airway-related MDRPI is influenced by multiple factors, including the duration of airway placement, use of SSD tubes, type of fixation device, and the moisture, mobility, and friction/shear subscale scores of the Braden Scale. The nomogram model developed through meta-analysis and a prospective cohort demonstrates favorable predictive performance and clinical net benefit. It provides an evidence-based tool to support nursing staff in early identification, stratified management, and precision prevention of MDRPI. To enhance the consistency and operability of model implementation in clinical practice, we recommend accompanying its rollout with standardized assessment forms, quality control checklists for airway fixation, and clearly defined processes for dynamic reassessment.

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