BMC Cardiovascular Disorders

RESEARCH

Open Access

A nomogram to predict congestive heart failure in patients with acute kidney injury: a retrospective study based on the MIMIC-III database

Quankuan Gu[1,2], Yucheng Qi[1,2], Yaxin Xiong[1,2], Xinyue Ma[1,2], Jun Lyu[3*†], Wei Yang[1,2*†], Xianglin Meng[1,2*†] and Mingyan Zhao[1,2*†]

Abstract

Object Objective: Acute Kidney Injury (AKI) is a renal disease marked by diminished urine output and elevated serum creatinine levels. AKI has a global incidence rate of about 20%, with an average mortality rate of 23%. Cardiovascular disease emerges as one of the primary causes of death associated with AKI. We developed a nomogram to estimate the probability of patients with AKI developing congestive heart failure.

Method We conducted a retrospective study of patients with AKI, using the MIMIC-III database. The patients were randomly divided into training and validation cohorts. Variables were selected via logistic regression, followed by the construction of the nomogram. The accuracy and sensitivity of the predictive model were verified using the Hosmer-Lemeshow test (HL) and the Area Under the Curve (AUC). The nomogram and SOFA scores were compared to APSIII using the Net Reclassification Index (NRI), Integrated Discrimination Improvement (IDI), Calibration curves, and Decision Curve Analysis (DCA).

Results The final study included 9,174 individuals. The multivariate logistic regression revealed a correlation between age, Systolic Blood Pressure (SBP), Partial Pressure of Oxygen (PO2), hemoglobin, Blood Urea Nitrogen (BUN), Chloride (Cl^-), cardiac arrhythmias, valvular heart disease, pulmonary circulation disease, chronic pulmonary disease, and diabetes. These factors are strongly associated with the development of congestive heart failure. Based on these findings, we created a nomogram. This nomogram has a higher predictive effect than the SOFA score and the

†Jun Lyu, Wei Yang, Xianglin Meng and Mingyan Zhao are the corresponding authors of this article.

*Correspondence:
Jun Lyu
lyujun2020@jnu.edu.cn
Wei Yang
icuyangwei@sina.com
Xianglin Meng
mengzi98@163.com
Mingyan Zhao
mingyan197@gmail.com

Full list of author information is available at the end of the article

APSIII score (AUC = 0.751, SOFA: 0.659, APSIII: 0.62). Its verification through NRI, IDI, and DCA demonstrated that this nomogram offers superior specificity and clinical prognosis compared to the SOFA score and APSIII score.

Keywords Acute kidney injury, Congestive heart failure, Prognosis, MIMIC-III, Nomogram

Introduction

Acute Kidney Injury (AKI), defined by the 2012 Kidney Disease Improving Global Outcomes (KDIGO) guidelines, is a nephron and renal impairment condition characterized by elevated creatinine levels and decreased urine output over a short term, typically less than 7 days [1]. A meta-analysis of data from 154 studies comprising 3,585,911 patients indicated an incidence rate of 8.3%, hospital-acquired AKI of 20-31.7%, and an average annual mortality rate from AKI around 23% [2]. The most common causes of death post-hospitalization in patients with AKI were cardiovascular disease and cancer, each accounting for 28% [3]. Simultaneously, patients with cardiovascular disease who had AKI witnessed a 38% hike in major cardiovascular events and an 86% increase in mortality rates compared to patients without AKI [4].

The kidneys and heart share many common pathways, such as inflammation, cellular immunity, stress, nutrition, and metabolism [5]. Owing to these bidirectional connections, the term "Cardio-renal syndrome" was coined [6, 7]. Acute kidney injury often results in fluid retention due to reduced glomerular filtration rate and the activation of the renin-angiotensin system. This is especially prevalent among patients with heart failure, presenting symptoms such as peripheral edema, pulmonary congestion, and third spatial effusion [8]. AKI often impacts cardiac function due to factors such as acidosis, hyperkalemia, urinary toxins, hypervolemia, hypertension, and systemic inflammation [9]. Post-AKI, the risk of heart failure escalates by 58% compared to patients without AKI [10], the likelihood of myocardial infarction surges by 40% [11, 12], and the incidence of cardiovascular disease after AKI tends to increase mortality [4]. The mortality rate is significantly higher in patients with AKI who experience cardiovascular events compared to those without cardiovascular disease [13]. Consequently, detecting early risk factors for heart failure and timely intervention can considerably impact the prognosis of patients with AKI.

A nomogram is a graphical tool based on a statistical predictive model that calculates the probability of a clinical event in an individual patient using several indicators [14]. In this study, we aim to develop a nomogram to predict the likelihood of congestive heart failure in patients with acute kidney injury. This tool could assist physicians to promptly identify high-risk factors for congestive heart failure in patients with AKI and better comprehend patients with cardio-renal syndrome.

Method

The Medical Information Mart for Intensive Care (MIMIC) III database is a comprehensive source of medical data for critically ill patients [15]. MIMIC-III includes data on more than 58,000 admissions to Beth Israel Deaconess Medical Center in Boston from 2001 to 2012 [16]. We obtained permission to access the database after completing the online training course of the National Health Protection Human Research Institute (certificate No.: 62299628). This retrospective study analyzed data from third-party anonymous, publicly available databases (MIMIC-III) and acquired approval from a pre-existing institutional review board. Patient information in the database was anonymized, thus informed consent was not required for the study. The report of this study adheres to the STROBE guidelines [17].

Study population

The study population was selected based on the diagnostic criteria for acute kidney injury. Patients diagnosed with acute kidney injury were extracted from the MIMIC-III database (version 1.4) derivative table. Exclusion criteria were as follows: (1) age < 18 years; (2) length of ICU stay < 24 h; (3) duplicate and incomplete data. We randomly selected 70% of the subjects for the training set and the remaining 30% of the subjects served as the validation set.

Exclusion criteria were based on the following considerations. (1) Patients aged < 18 years are not considered adults, and we have collected enough and enough samples to ignore this group of patients without affecting the final statistical results. (2) Patients admitted to the ICU less than 24 were not included in the study sample because they may not have collected sufficient information (e.g. laboratory indicators). The patients within 24 h of ICU admission have not undergone medical intervention, and the data collected during this period can basically reflect the most original state of the patient. (3) Repeated samples and samples with excessive missing data will affect the final statistical results, which were not included in the study. The data extraction process based on the inclusion criteria is depicted in Fig. 1.

Research method

We utilized SQL to extract the information from the MIMIC-III database. All these data corresponds to the 24 h prior to ICU admission. The primary outcome indicator was the probability of heart failure.

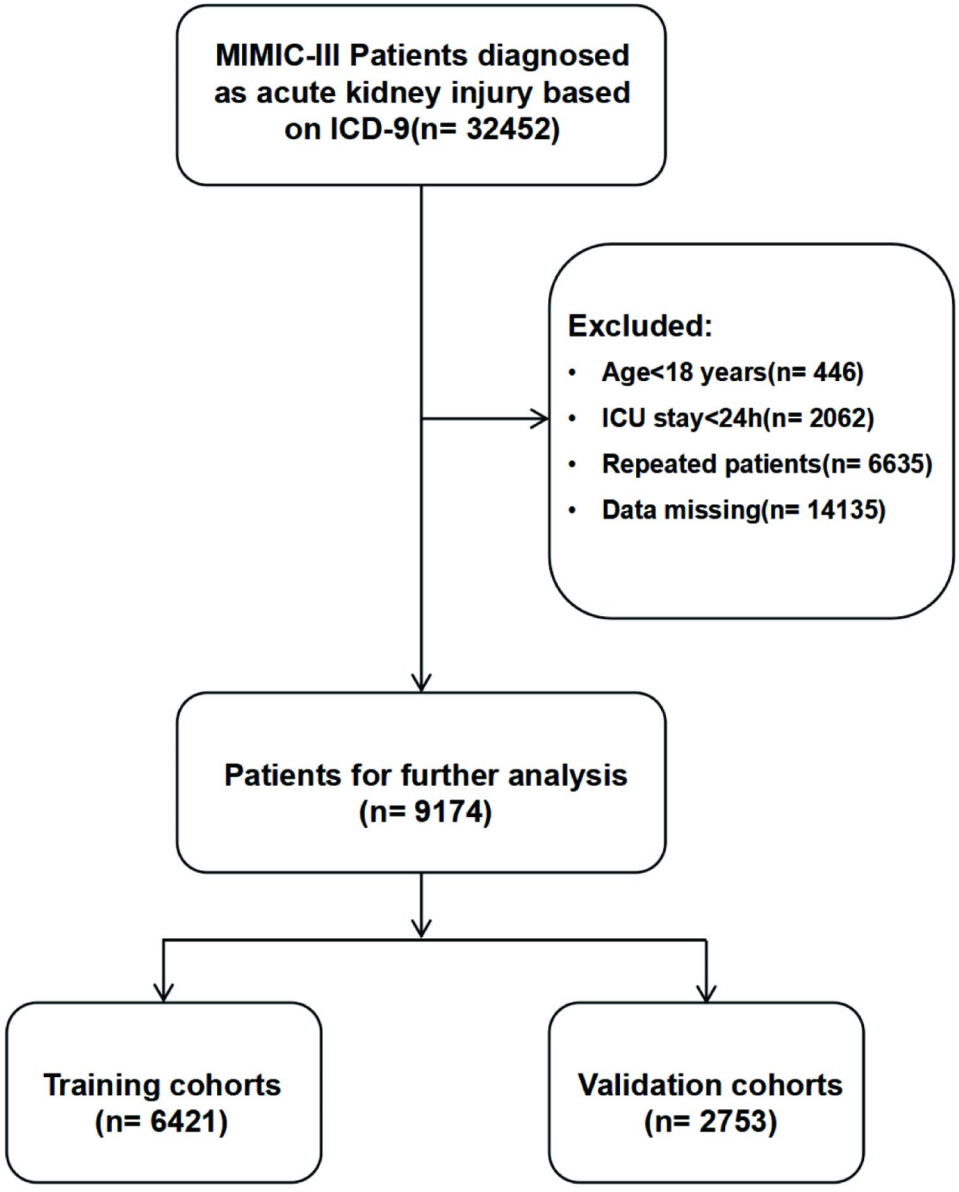

Fig. 1 Follow chat of study population selection. **MIMIC**: Medical Information Mart for Intensive Care; **ICD**: International Classification of Diseases

Statistical analysis

Continuous variables were represented by mean ± SD values or median and quartiles [M (Q1, Q3)]. Categorical variables were presented as percentages. Multivariate logistic regression was employed to select variables for the prediction model. The model's discriminative power was evaluated by comparing the area under the curve (AUC) of the nomogram, and existing SOFA and APSIII scores. The AUC ranges from 0 to 1. A value of 1 indicates perfect agreement and 0.5 indicates performance no better than chance. Larger AUC values denote a more accurate prognostic stratification [15]. Calibration curves were drawn to assess the model's agreement between predicted survival probability and observed adverse outcomes, and decision curve analysis (DCA) was used to verify the model's clinical validity.

All statistical analyses were conducted using R software version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria). All tests were two-sided, and a *P*-value less than 0.05 was considered statistically significant.

Result

Basic characteristics of the study subjects

A total of 32,452 patients met the screening criteria according to the ICD codes. After applying the exclusion criteria, 9,174 patients were included in the final data. These patients were randomized into Training cohorts ($n = 6421$) and Validation cohorts ($n = 2753$). All extracted

continuous variables did not conform to normal distribution, thus they were expressed by the median and quartiles [M (Q1, Q3)]. Basic characteristics of the patients are provided in Table 1. The Training cohort included 3,702 males (57.7%) and 2,719 females (42.3%), with a median age of 67 years (IQR = 55–78 years). The Validation cohort included 1,593 males (57.9%) and 1,169 females (42.1%), with a median age of 68 years (IQR = 55–78 years). The majority of patients in both cohorts were white (> 70%), and most admissions were emergencies (> 88%). The initial care unit for the majority was the MICU (37.4% vs. 38.1%). More than 58% of patients had health insurance. The median body temperature in both groups was 36.9℃ (IQR: 36.4–37.3℃), median heart rate was 88 bpm (IQR: 77–100 bpm), and median respiratory rate was 16 per min (IQR = 16–22 bpm). Median systolic blood pressure was 114mmHg (IQR = 105-126mmHg) and median diastolic blood pressure was 59mmHg (IQR = 52-65mmHg). Median oxygen saturation was 98% (IQR = 96–99%). The median SOFA score was 5 points (IQR = 3–8 points). The median APSIII score was 49 points (IQR = 36–65 points) and 50 points (IQR = 36–68 points), respectively. Median Glasgow Coma Scale (GCS) score was 9 (IQR = 4–14). Diagnosis of AKI within 48 h occurred in 8,078 patients (88.1%), including 1,966 patients (21.4%) with AKI Stage I, 3,822 patients (41.7%) with AKI Stage II, and 2,290 patients (25%) with AKI Stage III. Diagnosis of AKI 7 days post ICU admission occurred in 1,920 patients (20.9%) with AKI Stage I, 4,185 patients (45.6%) with AKI Stage II, and 3,069 patients (33.5%) with AKI Stage III.

Median PH values for the patients were 7.38 (IQR = 7.31–7.44) in both cohorts. The median partial pressure of oxygen was 128mmHg (IQR = 78-281mmHg) and 130mmHg (IQR = 77-273mmHg), and the median partial pressure of carbon dioxide was 40mmHg (IQR = 35-46mmHg) across both cohorts. Lactic acid levels were 1.8 mmol/L (IQR = 1.2–2.9 mmol/L) and 1.8 mmol/L (IQR = 1.3-3mmol/L). The patients exhibited elevated white blood cells, with counts of 13.7 K/μL (IQR = 10–18.8 K/μL) in both cohorts. The neutrophil ratio was 80.1% (IQR = 71–87%) and 80.5% (IQR = 71-87.1%). The median Prothrombin Time (PT) for patients was 13.9 s (IQR = 12.8–16.2 s) and 13.9 s (IQR = 12.9–16.3 s), while the median Partial Thromboplastin Time (PTT) was 29.8 s (IQR = 25.8–36.9 s) and 29.9 s (IQR = 25.9–37 s). The median Blood Urea Nitrogen (BUN) was 24 mg/dL (IQR = 16–40 mg/dL) and 25 mg/dL (IQR = 16–41 mg/dL), and the median creatinine was 1.1 mg/dL (IQR = 0.8–1.6 mg/dL) and 1.1 mg/dL (IQR = 0.8-1.7 mg/dL).

More than 60% of patients received mechanical ventilation on the first day of ICU admission, including 68.6% ($n = 4405$) of the Training cohort and 69.5% ($n = 1913$) of the Validation cohort. Vasopressors were used in 12.7% of patients ($n = 1168$). Only 5.6% of all patients ($n = 517$) received Continuous Renal Replacement Therapy (CRRT) on the first day of ICU admission. There were no significant differences in baseline clinicopathological data between groups. All missing values of data obtained in all patients were below 10% and were filled using the median. All-cause mortality in all patients was 24.1% ($n = 2210$), with 23.9% ($n = 1532$) in the Training cohort and 24.6% ($n = 678$) in the Validation cohort. The mortality rate in patients with concurrent Heart Failure (HF) was 26%, compared to 22.5% in AKI patients without heart failure. The median length of stay in the ICU was 5 days for both cohorts, with a median hospital stay of 13.5 days for the Training cohort and 12.9 days for the Validation cohort.

There were no significant differences in baseline clinicopathological data between the groups. Missing data, which accounted for less than 10% of all patient data, were imputed using the median value. The all-cause mortality rate for all patients was 24.1% ($n = 2210$). Among the training cohorts, the all-cause mortality during hospitalization was 23.9% ($n = 1532$), while the all-cause mortality for the validation cohorts during hospitalization was 24.6% ($n = 678$). Patients with combined Heart Failure (HF) had a mortality rate of 26%, compared to 22.5% for Acute Kidney Injury (AKI) patients without heart failure. The median length of hospital stay in the training cohorts was 13.5 days with a median Intensive Care Unit (ICU) stay of 5 days. For the validation cohorts, the median length of hospital stay was 12.9 days with a median ICU stay of 4.9 days.

According to the multifactorial logistic regression method, **age** (odds ratio [OR]: 1.03, 95% confidence interval [CI]:1.025–1.038, $P < 0.0001$); systolic blood pressure (**SBP**) (OR: 0.986, 95%CI: 0.979–0.993, $P < 0.0001$); partial pressure of oxygen (**PO_2**) (OR: 0.999, 95%CI: 0.998–0.999, $P < 0.0001$); hemoglobin (**Hb**) (OR: 0.792, 95%CI: 0.708–0.886, $P < 0.0001$); **BUN** (OR: 1.007, 95%CI: 1.003–1.01, $P < 0.0001$); chloride (**CL^-**) (OR: 0.974, 95%CI: 0.951–0.997, $P = 0.026$); **cardiac arrhythmias** (OR: 1.902, 95%CI: 1.673–2.163, $P < 0.0001$); **valvular heart disease** (OR: 2.225, 95%CI: 1.878–2.638, $P < 0.0001$); **pulmonary circulation disease** (OR: 1.432, 95%CI: 1.145–1.790, $P = 0.002$); Chronic Obstructive Pulmonary Disease (**COPD**) (OR: 1.289, 95%CI: 1.108-1.500, $P = 0.001$); and **Diabetes** (OR: 2.546, 95%CI: 1.989–3.261, $P < 0.0001$) were included in the predictive model. A nomogram was formulated based on these 11 selected variables, which allowed for estimation of the probability of sepsis occurrence (Fig. 2). Odds ratios for other indicators, 95%CI, and statistical measures are displayed in Table 2.

Table 1 Baseline characteristics of included participants

	All ($n=9174$)	Training cohorts ($n=6421$)	Validation cohorts ($n=2753$)	Statistics	*P*
Age, years, M (Q1, Q3)	67(55, 78)	67(55, 78)	68(55, 78)	Z= -0.0458	0.963
Gender, n(%)				$\chi^2=0.035$	0.852
Male	5295(57.7%)	3702 (57.7%)	1593 (57.9%)		
Female	3879(42.3%)	2719 (42.3%)	1160 (42.1%)		
Race, n(%)				$\chi^2=1.091$	0.779
White	6572(71.6%)	4617 (71.9%)	1955 (71%)		
Black	692(7.5%)	475 (7.4%)	217 (7.9%)		
Asian	200(2.2%)	137 (2.1%)	63 (2.3%)		
Other	1710(18.6%)	1192 (18.6%)	518 (18.8%)		
Admission, n(%)				$\chi^2=4.030$	0.133
EMERGENCY	8122(88.5%)	5660 (88.1%)	2462 (89.4%)		
ELECTIVE	764(8.3%)	559 (8.7%)	205 (7.4%)		
URGENT	288(3.1%)	202 (3.1%)	86 (3.1%)		
First careunit, n(%)				$\chi^2=3.278$	0.351
MICU	3450(37.6%)	2402 (37.4%)	1048 (38.1%)		
SICU	1651(18%)	1172 (18.3%)	479 (17.4%)		
CCU	1209(13.2%)	825 (12.8%)	384 (13.9%)		
Other	2864(31.2%)	2022 (31.5%)	842 (30.6%)		
Insurance, n(%)				$\chi^2=0.972$	0.808
Medicare	5378(58.6%)	3780 (58.9%)	1598 (58%)		
Private	2687(29.3%)	1866 (29.1%)	821 (29.8%)		
Medicaid	783(8.5%)	543 (8.5%)	240 (8.7%)		
Other	326(3.6%)	232 (3.6%)	94 (3.4%)		
Score, M (Q1, Q3)					
APSIII	49(36, 66)	49(36, 65)	50(36, 68)	Z= -1.7447	0.081
SOFA	5(3, 8)	5(3, 8)	5(3, 8)	Z= -2.5242	0.012
qSOFA	2(2, 2)	2(2, 2)	2(2, 2)	Z= -1.5532	0.120
SIRS	3(3, 4)	3(3, 4)	3(3, 4)	Z= -1.6879	0.091
GCS	9(4, 14)	9(4, 14)	9(4, 14)	Z= -0.6620	0.508
AKI_48h	8078(88.1%)	5636(87.8%)	2442(88.7%)	$\chi^2=1.971$	0.160
AKI_stage_48h				$\chi^2=2.431$	0.488
No	1096(11.9%)	785 (12.2%)	311 (11.3%)		
StageI	1966(21.4%)	1386 (21.6%)	580 (21.1%)		
StageII	3822(41.7%)	2650 (41.3%)	1172 (42.6%)		
StageIII	2290(25%)	1600 (24.9%)	690 (25.1%)		
AKI_stage_7d				$\chi^2=1.574$	0.455
StageI	1920(20.9%)	1365 (21.3%)	555 (20.2%)		
StageII	4185(45.6%)	2909 (45.3%)	1276 (46.3%)		
StageIII	3069(33.5%)	2147 (33.4%)	922 (33.5%)		
Vital signs					
Temperature, ℃, M (Q1, Q3)	36.9(36.4, 37.3)	36.9(36.4, 37.3)	36.9(36.5, 37.3)	Z= -0.5100	0.610
Heart rate, bpm, M (Q1, Q3)	88(78, 100)	88(77, 100)	88(78, 100)	Z= -2.2323	0.026
Respiratory rate, bpm, M (Q1, Q3)	19(16, 22)	19(16, 22)	19(16, 22)	Z= -2.4611	0.014
SBP, mmHg, M (Q1, Q3)	114(105, 126)	114(105, 126)	113(105, 126)	Z= -0.8212	0.412
DBP, mmHg, M (Q1, Q3)	59(52, 65)	59(52, 65)	59(52, 65)	Z= -0.6340	0.526
MAP, mmHg, M (Q1, Q3)	76(70, 83)	76(70, 83)	76(70, 83)	Z= -0.6115	0.541
SpO_2, %, M (Q1, Q3)	98(96, 99)	98(96, 99)	98(96, 99)	Z= -1.6326	0.103
Weight, Kg, M (Q1, Q3)	79(67, 94)	79(67, 94)	80(67, 94)	Z= -0.5844	0.559
Urine First Day, mL, M (Q1, Q3)	1437(842.25, 2280)	1460(850, 2290)	1397(825, 2260)	Z= -1.7362	0.083
Blood gas analysis					
PH, M (Q1, Q3)	7.38(7.31, 7.44)	7.38(7.31, 7.44)	7.38(7.3, 7.43)	Z= -3.7721	0.0001
PO_2, mmHg, M (Q1, Q3)	129(78, 278)	128(78, 281)	130(77, 273)	Z= -0.0266	0.979

Table 1 (continued)

	All (*n* = 9174)	Training cohorts (*n* = 6421)	Validation cohorts (*n* = 2753)	Statistics	*P*
PCO_2, mmHg, M (Q1, Q3)	40(35, 46)	40(35, 46)	40(35, 46)	Z= -0.5681	0.570
HCO_3^-, mmol/L, M (Q1, Q3)	24(21, 27)	24(21, 27)	24(21, 27)	Z= -2.3243	0.020
Lactate, mmol/L, M (Q1, Q3)	1.8(1.2, 2.9)	1.8(1.2, 2.9)	1.8(1.3, 3)	Z= -1.8204	0.069
Anion gap, mmol/L, M (Q1, Q3)	16(13, 19)	16(13, 19)	16(13, 19)	Z= -1.5260	0.127
Glucose, mg/dL, M (Q1, Q3)	134(116.17, 160.86)	134(116, 160.33)	133.91(116.42, 161.75)	Z= -0.3015	0.763
Laboratory test					
WBC, K/μL, M (Q1, Q3)	13.7(9.9, 18.8)	13.7(10, 18.8)	13.7(9.8, 18.8)	Z= -0.5279	0.598
Neutrophil, %, M (Q1, Q3)	80.2(71, 87)	80.1(71, 87)	80.5(71, 87.1)	Z= -0.8573	0.391
Lymphocytes, %, M (Q1, Q3)	10.6(6, 17.9)	10.5(6, 18)	10.8(6, 17.4)	Z= -0.9747	0.330
Monocyte, %, M (Q1, Q3)	4.2(2.9, 6)	4.2(2.9, 6)	4.1(2.9, 5.9)	Z= -0.2813	0.779
Hemoglobin, g/dL, M (Q1, Q3)	11.7(10.1, 13.3)	11.7(10.2, 13.3)	11.7(10, 13.3)	Z= -0.6295	0.529
Hematocrit, %, M (Q1, Q3)	34.7(30.5, 39.2)	34.7(30.5, 39.2)	34.7(30.4, 39.4)	Z= -0.0779	0.938
RDW, %, M (Q1, Q3)	14.5(13.6, 16.1)	14.5(13.5, 16.1)	14.6(13.6, 16.2)	Z= -0.8648	0.387
Platelet, K/μL, M (Q1, Q3)	226(160, 301)	226(161, 301)	225(158, 299)	Z= -0.9973	0.319
PT, sec, M (Q1, Q3)	13.9(12.9, 16.2)	13.9(12.8, 16.2)	13.9(12.9, 16.3)	Z= -0.8004	0.424
PTT, sec, M (Q1, Q3)	29.8(25.9, 36.9)	29.8(25.8, 36.9)	29.9(25.9, 37)	Z= -0.4837	0.629
INR, ratio, M (Q1, Q3)	1.2(1.1, 1.5)	1.2(1.1, 1.5)	1.2(1.1, 1.5)	Z= -0.4983	0.618
ALT, U/L, M (Q1, Q3)	27(16, 52)	26(16, 52)	27(16, 51)	Z= -0.0917	0.927
AST, U/L, M (Q1, Q3)	35(22, 73)	35(22, 73)	35(22, 74)	Z= -0.8982	0.369
Albumin, g/dL, M (Q1, Q3)	3.1(2.6, 3.7)	3.2(2.6, 3.7)	3.1(2.6, 3.6)	Z= -1.1969	0.231
Total bilirubin, mg/dL, M (Q1, Q3)	0.6(0.4, 1.1)	0.6(0.4, 1.1)	0.6(0.4, 1.1)	Z= -1.1025	0.270
Creatinine, mg/dL, M (Q1, Q3)	1.1(0.8, 1.7)	1.1(0.8, 1.6)	1.1(0.8, 1.7)	Z= -1.8402	0.066
BUN, mg/dL, M (Q1, Q3)	24(16, 40)	24(16, 40)	25(16, 41)	Z= -1.4909	0.136
Na^+, mmol/L, M (Q1, Q3)	138(135, 141)	138(135, 141)	138(135, 141)	Z= -1.7074	0.088
K^+, mmol/L, M (Q1, Q3)	4.2(3.8, 4.7)	4.2(3.8, 4.7)	4.2(3.8, 4.7)	Z= -0.0648	0.948
TotalCa^{2+}, mmol/L, M (Q1, Q3)	8.5(7.9, 9)	8.5(7.9, 9)	8.5(7.8, 9.1)	Z= -1.4068	0.159
FreeCa^{2+}, mmol/L, M (Q1, Q3)	1.11(1.05, 1.16)	1.11(1.05, 1.16)	1.11(1.04, 1.16)	Z= -0.9766	0.329
CL^-, mmol/L, M (Q1, Q3)	103(99, 106)	103(99, 106)	103(99, 106)	Z= -2.0947	0.036
Complication					
Congestive heart failure, n(%)	3130(34.1%)	2197(34.2%)	933(33.8%)	$\chi^2 = 0.045$	0.831
Cardiac arrhythmias, n(%)	3926(42.8%)	2721 (42.4%)	1205 (43.8%)	$\chi^2 = 1.529$	0.216
Valvular heart disease, n(%)	1243(13.5%)	889 (13.8%)	354 (12.9%)	$\chi^2 = 1.601$	0.206
Pulmonary circulation disease, n(%)	777(8.5%)	529 (8.2%)	248 (9%)	$\chi^2 = 1.473$	0.225
Peripheral vascular disease, n(%)	881(9.6%)	611 (9.5%)	270 (9.8%)	$\chi^2 = 0.189$	0.664
Hypertension, n(%)	4938(53.8%)	3437 (53.5%)	1501 (54.5%)	$\chi^2 = 0.767$	0.381
Paralysis, n(%)	294(3.2%)	217 (3.4%)	77 (2.8%)	$\chi^2 = 2.108$	0.147
Other neurological, n(%)	1284(14%)	917 (14.3%)	367 (13.3%)	$\chi^2 = 1.446$	0.229
Chronic pulmonary disease, n(%)	2088(22.8%)	1431 (22.3%)	657 (23.9%)	$\chi^2 = 2.731$	0.098
Diabetes, n(%)	1996(21.8%)	1387 (21.6%)	609 (22.1%)	$\chi^2 = 0.306$	0.580
Hypothyro, n(%)	895(9.8%)	649 (10.1%)	246 (8.9%)	$\chi^2 = 3.005$	0.083
Renal failure, n(%)	1548(16.9%)	1090 (17%)	458 (16.6%)	$\chi^2 = 0.158$	0.691
Liver disease, n(%)	1506(16.4%)	1049 (16.3%)	457 (16.6%)	$\chi^2 = 0.097$	0.755
Peptic ulcer, n(%)	77(0.8%)	55 (0.9%)	22 (0.8%)	$\chi^2 = 0.076$	0.782
AIDS, n(%)	64(0.7%)	45 (0.7%)	19 (0.7%)	$\chi^2 = 0.003$	0.955
lymphoma, n(%)	146(1.6%)	102 (1.6%)	44 (1.6%)	$\chi^2 = 0.001$	0.973
Metastatic cancer, n(%)	553(6.0%)	400 (6.2%)	153 (5.6%)	$\chi^2 = 1.536$	0.215
Solid tumor, n(%)	299(3.3%)	199 (3.1%)	100 (3.6%)	$\chi^2 = 1.737$	0.187
Rheumatoid arthritis, n(%)	326(3.6%)	224 (3.5%)	102 (3.7%)	$\chi^2 = 0.264$	0.608
Coagulopathy, n(%)	1746(19.0%)	1205 (18.8%)	541 (19.7%)	$\chi^2 = 0.979$	0.323
Obesity, n(%)	572(6.2%)	401 (6.2%)	171 (6.2%)	$\chi^2 = 0.004$	0.951
Weight loss, n(%)	732(8.0%)	509 (7.9%)	223 (8.1%)	$\chi^2 = 0.079$	0.779
Fluid electrolyte, n(%)	3839(41.8%)	2673 (41.6%)	1166 (42.4%)	$\chi^2 = 0.416$	0.519

Table 1 (continued)

	All (*n* = 9174)	Training cohorts (*n* = 6421)	Validation cohorts (*n* = 2753)	Statistics	*P*
Blood loss anemia, n(%)	221(2.4%)	157 (2.4%)	64 (2.3%)	$\chi^2 = 0.119$	0.730
Deficiency anemias, n(%)	263(2.9%)	182 (2.8%)	81 (2.9%)	$\chi^2 = 0.080$	0.777
Alcohol abuse, n(%)	890(9.7%)	627 (9.8%)	263 (9.6%)	$\chi^2 = 0.099$	0.754
Drug abuse, n(%)	383(4.2%)	270 (4.2%)	113 (4.1%)	$\chi^2 = 0.048$	0.826
Psychoses, n(%)	158(1.7%)	115 (1.8%)	43 (1.6%)	$\chi^2 = 0.597$	0.440
Depression, n(%)	811(8.8%)	552 (8.6%)	259 (9.4%)	$\chi^2 = 1.573$	0.210
Intervention					
Ventilation first day, n(%)	6318(68.9%)	4405 (68.6%)	1913 (69.5%)	$\chi^2 = 0.704$	0.402
Vasppressor, n(%)	1168(12.7%)	787 (12.3%)	381 (13.8%)	$\chi^2 = 4.345$	0.037
CRRT first day, n(%)	517(5.6%)	330 (5.1%)	187 (6.8%)	$\chi^2 = 9.903$	0.002
EN, n(%)	3161(34.5%)	2191 (34.1%)	970 (35.2%)	$\chi^2 = 1.055$	0.304
PN, n(%)	1446(15.8%)	1021 (15.9%)	425 (15.4%)	$\chi^2 = 0.311$	0.577
LOS OF hospital, days, M (Q1, Q3)	13.3(8, 21.87)	13.5(8, 22)	12.9(8, 21.6)	Z= -1.3067	0.191
LOS OF ICU, days, M (Q1, Q3)	5(2.7, 10.5)	5.1(2.7, 10.5)	4.9(2.7, 10.3)	Z= -1.3471	0.178
Death, n(%)	2210(24.1%)	1532 (23.9%)	678 (24.6%)	$\chi^2 = 0.622$	0.430

ALT: Alanine aminotransferase, **APSIII**: Acute Physiology Score III, **AST**: Aspartate aminotransferase, **bpm**: Beats per minute; **BUN**: Blood urea nitrogen, **Ca^{2+}**: Serum calcium, **CCU**: Cardiac care unit, **CRRT**: Continuous Renal Replacement Therapy, **DBP**: Diastolic blood pressure, **GCS**: Glasgow Coma Scale, **ICU**: Intensive care unit, **INR**: International normalized ratio, **K^+**: Serum potassium, **LDH**: Lactate dehydrogenase, **LOS**: Lengths of stay, **M**: Median, **MAP**: Mean arterial pressure, **MICU**: Medical intensive care unit, **Na^+**: Serum sodium, **PT**: Prothrombin time, **PTT**: Partial thromboplastin time, **Q1**: 1st quartile, **Q3**: 3st quartile, **RDW**: Red blood cell volume distribution width, **SBP**: Systolic blood pressure, **SICU**: Surgical intensive care unit, **SIRS**: Systemic inflammatory response syndrome, **SOFA**: Sequential Organ Failure Assessment, **SpO_2**: eripheral oxygen saturation, **WBC**: White blood cell, **Z**: Wilcoxon rank sum test, **χ^2**: Chi-square test

Discriminative ability of the nomogram

The performance of the nomogram was evaluated using the Hosmer-Lemeshow (HL) test, Area Under the Curve (AUC), Net Reclassification Improvement (NRI), and Integrated Discrimination Improvement (IDI) metrics. The HL test yielded a *P* value of 0.367 ($\chi^2 = 9.803$) for the Training cohort and a *P*-value of 0.871 ($\chi^2 = 4.555$) for the Validation cohort, showing a good fit for our model. The AUC was used to validate the nomogram in comparison to the Sequential Organ Failure Assessment (SOFA) score and the Acute Physiology Score III (APSIII) score. The AUC for the training set (Fig. 3A) and validation set (Fig. 3B) were 0.751 (SOFA: 0.659, APSIII: 0.62) and 0.749 (SOFA: 0.649, APSIII: 0.607), respectively. The NRI values for the Training cohort were 54.9% (95%CI: 50.2–60.2%) against SOFA score and 64.4% (95%CI: 59.4–68.6%) against APSIII score. For the Validation cohort, the NRI values were 57.1% (95%CI: 50-65.5%) against SOFA score and 66% (95%CI: 60.2–74.6%) against APSIII score. IDI values for the Training cohort were 10.58% (95%CI: 9.76–11.4%) versus SOFA score and 12.5% (95%CI: 11.42–13.07%) versus APSIII score. For the Validation cohort, the IDI values were 10.68% (95%CI: 9.42–11.93%) versus SOFA score and 13% (95%CI: 11.74–14.26%) versus APSIII score. All results were statistically significant (Table 3).

Nomogram calibration

Calibration The calibration curves for the Training and Validation cohorts, after bootstrapping, are shown in Fig. 4. The figure shows that both the bias-corrected curves and the apparent curves only slightly deviate from the reference line, suggesting a good agreement between the predicted and observed values in both cohorts.

The clinical value of the model and its impact on actual decision-making were validated by using DCA. In both training and validation groups, the net benefit of the nomogram was significantly greater than that of the SOFA and APSIII scores (Fig. 5), indicating the nomogram is useful in predicting the probability of heart failure.

Discussion

A search of the MIMIC-III database identified 32,452 patients who met the diagnostic criteria for acute kidney injury, and 9,174 ultimately met the criteria for inclusion in our study. We conducted more than 10 randomizations and selected the factor with the most repeated occurrence to include in the predictive model. Based on the information of these patients with acute kidney injury, we found that age, SBP, PO_2, hemoglobin, BUN, CL^-, cardiac arrhythmias, valvular heart disease, pulmonary circulation disease, COPD, and diabetes were closely associated with the occurrence of congestive heart failure. These data are all available within 24 h of patient admission to the ICU. After obtaining these data, through the nomogram we designed, the medical staff can judge the probability of heart failure in the AKI patient. This tool can identify patients at high risk of heart failure through simple history inquiries and blood tests.

In the current study, more researchers focused on the prediction of AKI in patients with heart failure [18, 19].

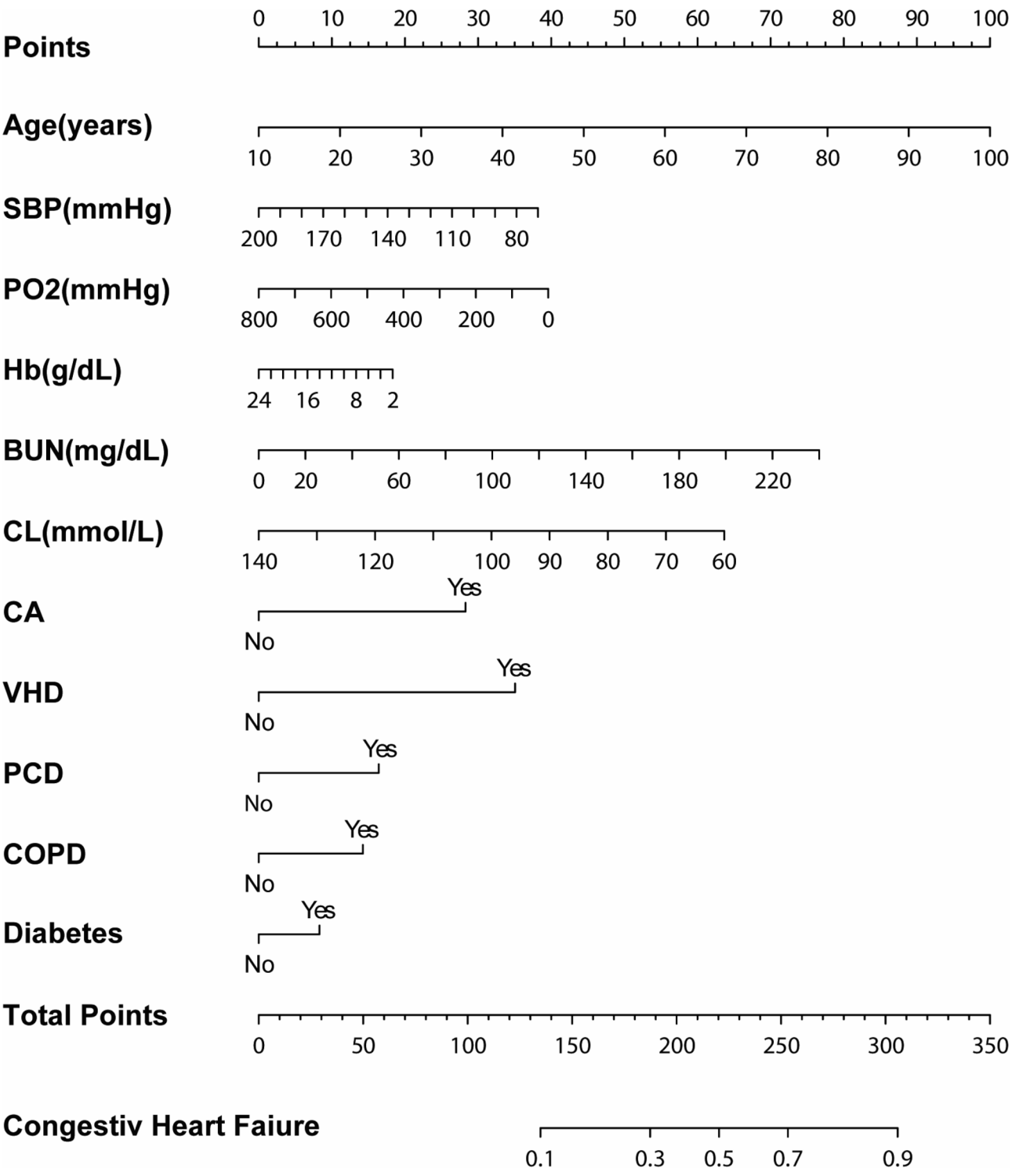

Fig. 2 Nomogram for predicting the probability of congestive heart failure. Left column shows the points bar (top) and eight parameters, each to be scored with a vertical line to the points bar, according to the different parameter values. The sum of the points is calculated (total points range, 0–350), and a vertical line is drawn from the total points bar to the diagnostic possibility below, to obtain probability of congestive heart failure

However, the prediction model of heart failure in AKI patients is relatively poorly studied. Our study fills in this gap. AKI is a significant risk factor for the development of heart failure, with heart failure occurring in 18% of AKI patients [13], in our study, this rate was 34.1%. The risk of heart failure typically increases with age. In some studies, the risk of heart failure was reported to be 5–9% in the general population [20, 21]. Similarly, in our study, age

Table 2 Selected variables analysed by multivariable logistic regression in the training cohort

	OR	95% CI	*P*
Age	1.03	1.025–1.038	< 0.001****
Gender			
Male	reference		
Female	1.197	1.046–1.371	0.009**
APSIII	0.999	0.994–1.003	0.606
SOFA	1.032	1.002–1.063	0.035*
qSOFA	0.941	0.843–1.051	0.279
SIRS	1.000	0.925–1.082	0.996
GCS	1.000	0.985–1.015	0.981
Temperature, ℃	0.995	0.903–1.096	0.920
Heart rate, min-1	1.003	0.998–1.007	0.294
Respiratory rate, min-1	1.014	0.998–1.031	0.090
SBP, mmHg	0.986	0.979–0.993	< 0.001****
DBP, mmHg	0.994	0.980–1.008	0.415
MAP, mmHg	1.015	0.998–1.033	0.089
SpO^2, %	0.997	0.971–1.024	0.813
Weight, Kg	1.002	0.999–1.006	0.127
PH	0.845	0.352–2.044	0.708
PO^2, mmHg	0.999	0.998–0.999	< 0.001****
PCO^2, mmHg	1.005	0.998–1.012	0.153
HCO^{3-}, mmol/L	1.008	0.985–1.031	0.517
Lactate, mmol/L	0.965	0.93–1.001	0.060
Anion gap, mmol/L	1.001	0.981–1.022	0.893
Glucose, mg/dL	0.999	0.997- 1.000	0.168
WBC, K/μL	1.000	0.995–1.005	0.932
Neutrophil, %	1.010	1.003–1.018	0.004***
Lymphocytes, %	1.012	1.003–1.022	0.008**
Monocyte, %	1.017	0.997–1.037	0.095
Hemoglobin, g/dL	0.792	0.708–0.886	< 0.001****
Hematocrit, %	1.080	1.039–1.123	< 0.001****
Platelet, K/μL	1.000	0.999- 1.000	0.192
PT, sec	1.014	1.001–1.028	0.041*
PTT, sec	1.002	0.999–1.005	0.171
INR, ratio	0.933	0.863–1.004	0.060
ALT, U/L	1.000	1.000–1.000	0.420
AST, U/L	1.000	1.000–1.000	0.680
Albumin, g/dL	1.023	0.918–1.14	0.680
Total bilirubin, mg/dL	0.961	0.939–0.982	< 0.001****
Creatinine, mg/dL	0.984	0.931–1.036	0.558
BUN, mg/dL	1.007	1.003–1.01	< 0.001****
Na+, mmol/L	1.006	0.98–1.032	0.666
K+, mmol/L	0.985	0.91–1.065	0.697
TotalCa2+, mmol/L	0.987	0.915–1.064	0.731
FreeCa2+, mmol/L	0.861	0.465–1.588	0.634
CL^-, mmol/L	0.974	0.951–0.997	0.026*
Cardiac arrhythmias	1.902	1.673–2.163	< 0.001****
VHD	2.225	1.878–2.638	< 0.001****
Pulmonary circulation disease	1.432	1.145–1.790	0.002***
Peripheral vascular disease	1.042	0.853–1.271	0.686
Hypertension	0874	0.766–0.999	0.048*
Paralysis	0.684	0.463–0.991	0.049*
Chronic pulmonary	1.289	1.108- 1.500	0.001***
Diabetes	2.546	1.989–3.261	< 0.001****

Table 2 (continued)

	OR	95% CI	*P*
Hypothyro	0.901	0.741–1.095	0.298
Renal failure	1.584	1.323–1.899	< 0.001****
Liver disease	0.945	0.770–1.158	0.585
Peptic ulcer	1.137	0.602–2.110	0.687
Metastatic cancer	0.530	0.398–0.699	< 0.001****
Obesity	1.123	0.859–1.465	0.396
Weight loss	0.658	0.514–0.837	0.001***
Blood loss anemia	0.911	0.609–1.349	0.644
Deficiency anemias	0.936	0.651–1.336	0.718
Alcohol abuse	0.938	0.732–1.197	0.610
Drug abuse	1.078	0.760–1.514	0.669
VentilationFirstDay	0.941	0.791–1.120	0.494
Vasppressor	0.852	0.690–1.051	0.136
CRRTFirstDay	0.801	0.583–1.097	0.168
EN	1.115	0.964–1.289	0.143
PN	1.073	0.891–1.290	0.456

ALT: Alanine aminotransferase, **APSIII**: Acute Physiology Score III, **AST**: Aspartate aminotransferase, **BUN**: Blood urea nitrogen, **Ca^{2+}**: serum calcium, **DBP**: Diastolic blood pressure, **GCS**: Glasgow Coma Scale, **INR**: International normalized ratio, **K^{+}**: serum potassium, **LDH**: Lactate dehydrogenase, **LOS**: Lengths of stay, **MAP**: Mean arterial pressure, **Na^{+}**: serum sodium, **PT**: Prothrombin time, **PTT**: Partial thromboplastin time, **RDW**: Red blood cell volume distribution width, **SBP**: Systolic blood pressure, **SICU**: Surgical intensive care unit, **SIRS**: systemic inflammatory response syndrome, **SOFA**: Sequential Organ Failure Assessment, **SpO_2**: peripheral oxygen saturation, **WBC**: White blood cell, *: <0.05, **: <0.01, ***: <0.005, ****: <0.001

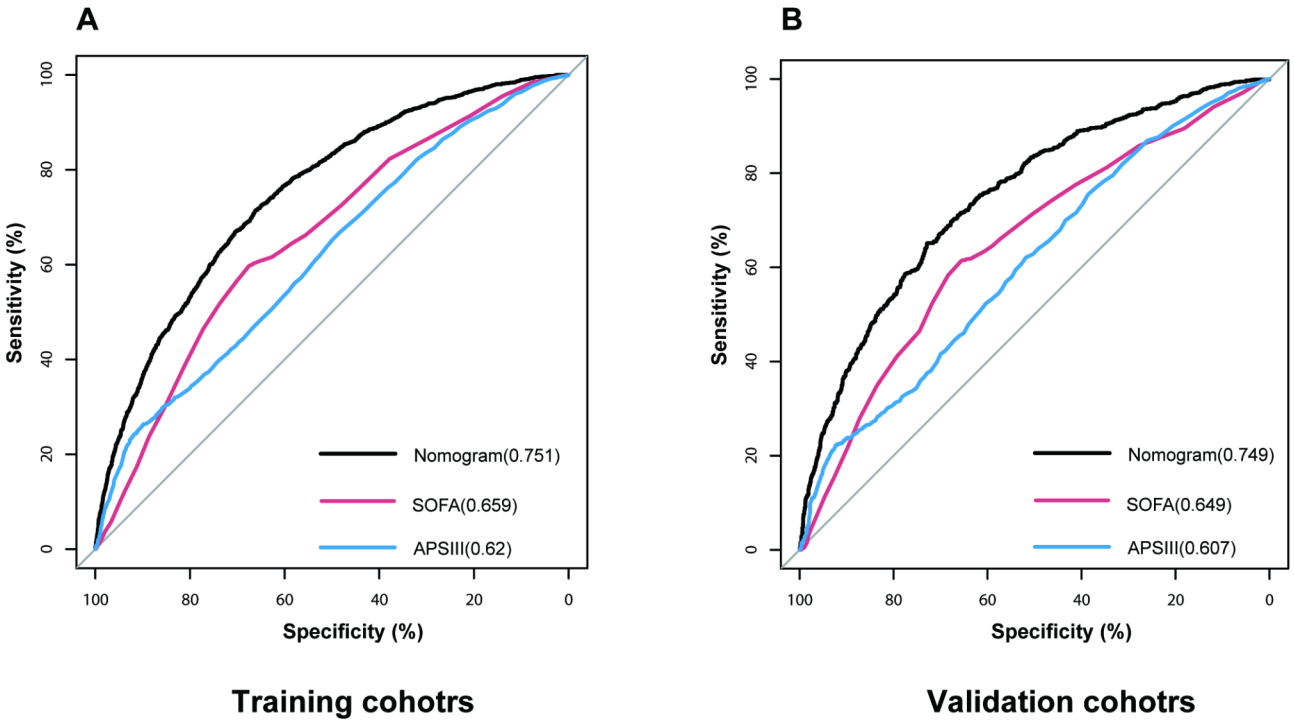

Fig. 3 Receiver operating characteristic (ROC) curves for the nomogram 、 SOFA and APSIII, showing AUCs for predicting the probability of congestive heart failure. **(A)**: training cohort; **(B)** validation cohort; **AUC**: area under the curve. **APSIII**: Acute physiology score III; **SOFA**: Sequential Organ Failure Assessment

was a risk factor for developing heart failure in patients with AKI. More than 90% of erythropoietin (EPO) in adults is produced by peritubular cells through mechanisms such as hypoxia-inducible factors (HIFs) [22], Since the kidney cannot synthesize normal EPO, symptoms of anemia are often observed in patients with renal failure. In our study, early onset of anemia predicted an increased incidence of heart failure. Other studies have found anemia to be an independent risk factor predicting longer hospital stays, higher rehospitalization rates,

Table 3 The AUC, NRI and IDI of SOFA, APSIII and Nomogram in training set and validation set

	AUC		NRI		IDI	
Training cohorts	**95%CI**	***P***	**95%CI**	***P***	**95%CI**	***P***
Nomogram	0.751(0.739–0.763)					
SOFA	0.659(0.645–0.673)	< 0.001(Z = 14.346)	0.549(0.502–0.602)	< 0.001(Z = 22.388)	10.58%(9.76- 11.4%)	< 0.001
APSIII	0.62(0.606–0.635)	< 0.001(Z = 17.749)	0.644(0.594–0.686)	< 0.001(Z = 27.236)	12.25%(11.42- 13.07%)	< 0.001
Validation cohorts						
Nomogram	0.749(0.729–0.768)					
SOFA	0.649(0.628–0.671)	< 0.001(Z = 9.718)	0.571(0.5- 0.655)	< 0.001(Z = 14.508)	10.68%(9.42- 11.93%)	< 0.001
APSIII	0.607(0.585–0.629)	< 0.001(Z = 12.175)	0.66(0.602–0.746)	< 0.001(Z = 18.323)	13%(11.74%- 14.26)	< 0.001

AUC: Area Under Curve, **IDI**: Integrated Discrimination Improvement, **NRI**: Net Reclassification Index

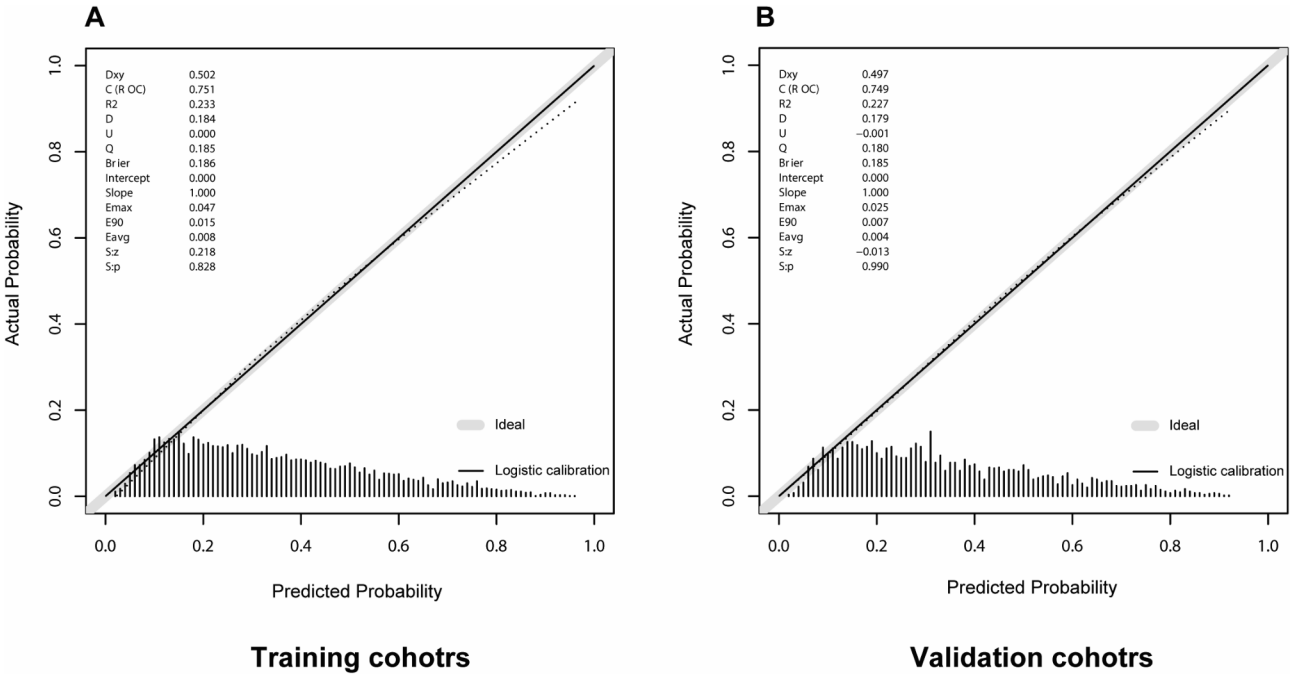

Fig. 4 Calibration curves for predicting the probability of congestive heart failure. In both sets, the apparent curve and bias-corrected curve slightly deviated from reference line, but a good conformity between observation and prediction is observed. **(A)**: Training cohort; **(B)**: Validation cohort

and worse outcomes in patients with heart failure [23, 24]. Blood Urea Nitrogen (BUN), a compound other than protein in human plasma, is excreted from the glomerulus. In patients with AKI, elevated BUN levels are predictive of systemic circulation congestion, which can lead to the development of heart failure. BUN to creatinine ratio (BUN/Scr) of more than 19.37 could be used as an independent risk factor for predicting all-cause mortality in chronic heart failure [25]. High BUN is an independent predictor of all-cause mortality in heart failure, whereas low BUN is associated with better outcomes [26]. Chloride, the most abundant extracellular anion in the body, plays a critical role in maintaining acid-base balance through its inverse relationship and homeostasis with bicarbonate. Our study suggests low chloride levels lead to the development of heart failure, which is consistent with previous findings [27], hypochloremia also increases cardiovascular mortality in the general population [28].

We analyzed 29 comorbidities in AKI patients, namely cardiac arrhythmias, valvular heart disease, pulmonary circulation disease, chronic pulmonary disease, and diabetes were included in the nomogram. These conditions are common precipitating factors for heart failure, yet surprisingly, hypertension was not included. Our analysis suggested that lower systolic blood pressure in patients with AKI is correlated with an increased risk of heart failure. A retrospective meta-analysis revealed that for every 10mmHg decrease in systolic blood pressure, the likelihood of major cardiovascular events, coronary heart disease, heart failure decreased, and there was a 13% reduction in cardiovascular mortality (RR: 0.87, 95%CI: 0.84–0.91), but this had no impact on renal failure [29]. In another study, patients with systolic blood pressure less than 120 mmHg had the highest risk of death at each time point (60-day, 180-day, 365-day) [30]. Combined with our study, it seems that AKI patients should

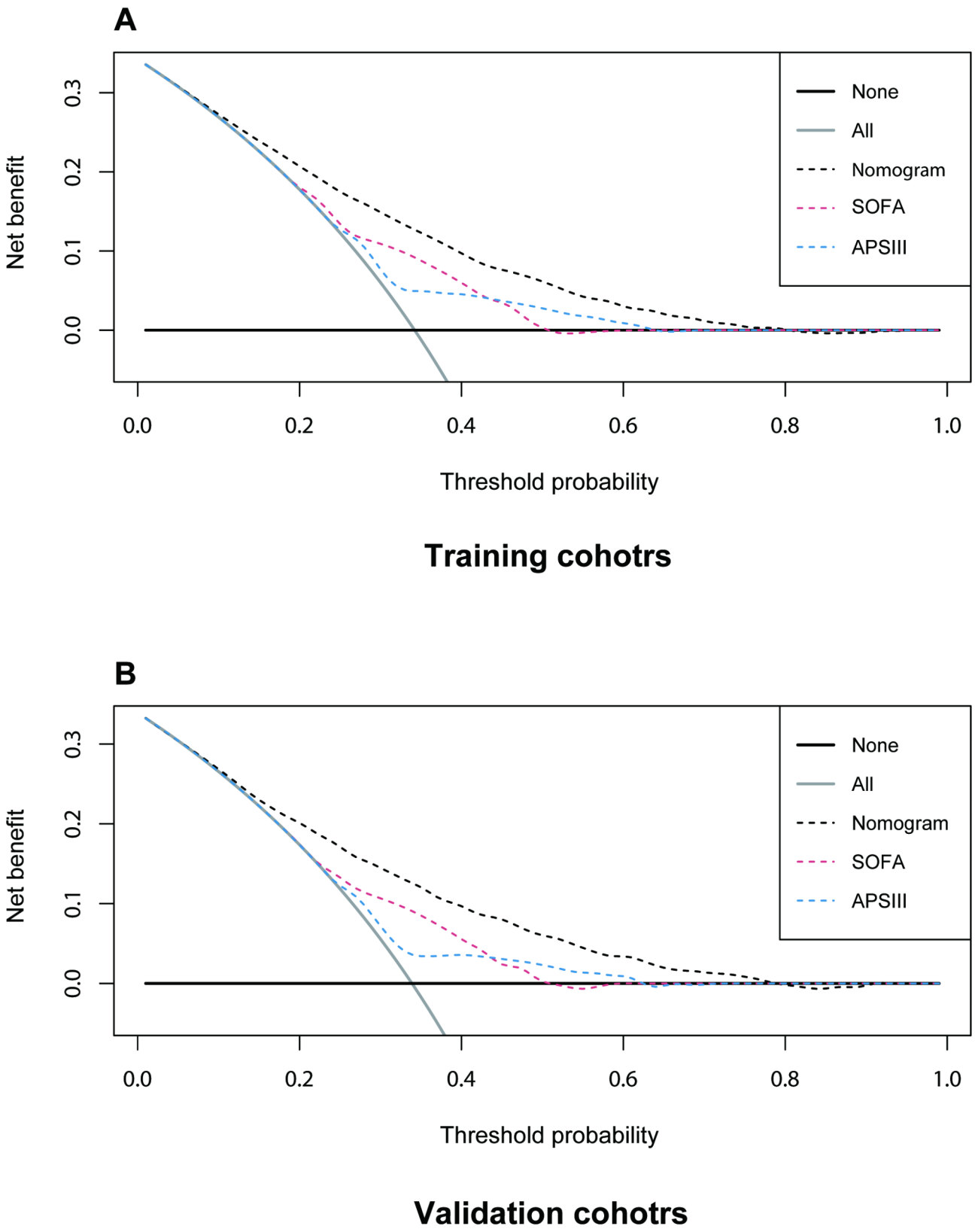

Fig. 5 Decision-curve analysis of the nomogram for predicting the probability of congestive heart failure. In all figures the black line is above the red line and blue line, showing that the area under the curve is larger for the new nomogram model than for the SOFA and APSIII. **(A)**: Training cohort; **(B)**: Validation cohort; **APSIII**: Acute physiology score III; **SOFA**: Sequential Organ Failure Assessment; **Black dotted line**: nomogram model; **Red dotted line**: SOFA model; **Blue dotted line**: APSIII

maintain a higher blood pressure level, however, more research is needed to validate this finding.

Limitations: Our study has several limitations. First, it is a retrospective analysis using clinical data extracted from the MIMIC-III database and it was not validated using other databases or clinical experiments. Second, the indicators included in the study focused on the physiological parameters within the first 24 h of ICU admission, without sufficient consideration of the treatments received by the patients, particularly pharmacological treatments. Thirdly, our prediction model was only validated within the MIMIC-III database. Future research should test the model using external data. Finally, our experiment only provided the basic medical history information and the basic biochemical indicators. No more indicators are absorbed (such as hemodynamic indicators, etc.). As Emilie Han's study pointed out, renin has a certain correlation with the occurrence of heart failure [31]. In our future research, we will use our hospital's own patient information to test this prediction model, and more predictive indicators will be included to improve this model.

Conclusion

We developed a nomogram that uses age, SBP, PO_2, hemoglobin, BUN, chloride, cardiac arrhythmias, valvular heart disease, pulmonary circulation disease, chronic pulmonary disease, and diabetes as predictive indicators for the occurrence of congestive heart failure. This model can assist healthcare providers in early identification of the risk of congestive heart failure in patients with AKI and facilitate earlier interventions.

Abbreviations

AKI	Acute Kidney Injury
ALT	Alanine aminotransferase
APSIII	Acute Physiology Score III
AST	Aspartate aminotransferase
AUC	Area Under the Curve
BUN	Blood urea nitrogen
Ca^{2+}	Serum calcium
CCU	Cardiac care unit
CI	Confidence intervals
CRRT	Continuous Renal Replacement Therapy
DBP	Diastolic blood pressure
DCA	Decision Curve Analysis
EPO	Erythropoietin
GCS	Glasgow Coma Scale
HIFs	Hypoxia-inducible factors
HL	Hosmer-Lemeshow test
ICU	Intensive care unit
IDI	Integrated Discrimination Improvement
INR	International normalized ratio
IQR	Interquartile range
K^+	Serum potassium
LDH	Lactate dehydrogenase
LOS	Lengths of stay
MAP	Mean arterial pressure
MICU	Medical intensive care unit
MIMIC	Medical Information Mart for Intensive Care
Na^+	Serum sodium
NRI	Net Reclassification Index
OR	Odds ratio
PT	Prothrombin time
PTT	Partial thromboplastin time
RDW	Red blood cell volume distribution width
SBP	Systolic blood pressure
SICU	Surgical intensive care unit
SIRS	Systemic inflammatory response syndrome
SOFA	Sequential Organ Failure Assessment
SpO_2	eripheral oxygen saturation
WBC	White blood cell
Z	Wilcoxon rank sum test
χ^2	Chi-square test

Acknowledgements

We would like to thank the participants, developers and investigators associated with the Medical Information Mart for Intensive Care (MIMIC)-III database.

Author contributions

Quankuan Gu designed and directed the study. Quankuan Gu and Yaxin Xiong extracted the data from the MIMIC-III database. Quankuan Gu, Yucheng Qi and Xinyue Ma collated and analyzed the data. Quankuan Gu and Yucheng Qi prepared the manuscript and designed the figures. All authors provided critical feedback and helped to shape the manuscript.

Funding

This research was supported by Heilongjiang Province Key R&D Program(GA21C011) and the National Natural Scientific Foundation of China [82172164] and Heilongjiang Province Key R&D Program(JD22C005).

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author. The names of the repository/repositories and accession number(s) can be found below: https://physionet.org/content/mimiciii/1.4/.

Declarations

Ethics approval and consent to participate

Considering that this study was based on the analysis of an anonymous third-party public database with prior approval from the Institutional Review Board, no ethical review was required. This study obtained informed consent from all study participants.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Critical Care Medicine, the First Affiliated Hospital of Harbin Medical University, Harbin Medical University, Harbin 150001, Heilongjiang Province, China
[2]Heilongjiang Provincial Key Laboratory of Critical Care Medicine, No. 2075, Qunli Seventh Avenue, Daoli District, Harbin 150001, Heilongjiang Province, China
[3]Department of Clinical Research, The First Affiliated Hospital of Jinan University, Guangzhou 510630, China

Received: 5 December 2024 / Accepted: 11 February 2025
Published online: 25 February 2025

References

1. Kellum JA, Romagnani P, Ashuntantang G, Ronco C, Zarbock A, Anders HJ. Acute kidney injury. Nat Rev Dis Primers. 2021;7(1):52. https://doi.org/10.1038/s41572-021-00284-z.

2. Susantitaphong P, Cruz DN, Cerda J, Abulfaraj M, Alqahtani F, Koulouridis I, et al. World incidence of AKI: a meta-analysis. Clin J Am Soc Nephrol. 2013;8(9):1482–93. https://doi.org/10.2215/CJN.00710113.
3. Silver SA, Harel Z, McArthur E, Nash DM, Acedillo R, Kitchlu A, et al. Causes of death after a hospitalization with AKI. J Am Soc Nephrol. 2018;29(3):1001–10. https://doi.org/10.1681/ASN.2017080882.
4. Odutayo A, Wong CX, Farkouh M, Altman DG, Hopewell S, Emdin CA, et al. AKI and Long-Term Risk for Cardiovascular events and mortality. J Am Soc Nephrol. 2017;28(1):377–87. https://doi.org/10.1681/ASN.2016010105.
5. Schefold JC, Filippatos G, Hasenfuss G, Anker SD, von Haehling S. Heart failure and kidney dysfunction: epidemiology, mechanisms and management. Nat Rev Nephrol. 2016;12(10):610–23. https://doi.org/10.1038/nrneph.2016.113.
6. Whitman IR, Feldman HI, Deo R. CKD and sudden cardiac death: epidemiology, mechanisms, and therapeutic approaches. J Am Soc Nephrol. 2012;23(12):1929–39. https://doi.org/10.1681/ASN.2012010037.
7. Palazzuoli A, Ronco C. Cardio-renal syndrome: an entity cardiologists and nephrologists should be dealing with collegially. Heart Fail Rev. 2011;16(6):503–8. https://doi.org/10.1007/s10741-011-9267-x.
8. Prowle JR, Kirwan CJ, Bellomo R. Fluid management for the prevention and attenuation of acute kidney injury. Nat Rev Nephrol. 2014;10(1):37–47. https://doi.org/10.1038/nrneph.2013.232.
9. Di Lullo L, Reeves PB, Bellasi A, Ronco C. Cardiorenal Syndrome in Acute kidney Injury. Semin Nephrol. 2019;39(1):31–40. https://doi.org/10.1016/j.semnephrol.2018.10.003.
10. Kottgen A, Russell SD, Loehr LR, Crainiceanu CM, Rosamond WD, Chang PP, et al. Reduced kidney function as a risk factor for incident heart failure: the atherosclerosis risk in communities (ARIC) study. J Am Soc Nephrol. 2007;18(4):1307–15. https://doi.org/10.1681/ASN.2006101159.
11. Gammelager H, Christiansen CF, Johansen MB, Tonnesen E, Jespersen B, Sorensen HT. Three-year risk of cardiovascular disease among intensive care patients with acute kidney injury: a population-based cohort study. Crit Care. 2014;18(5):492. https://doi.org/10.1186/s13054-014-0492-2.
12. Wu VC, Wu CH, Huang TM, Wang CY, Lai CF, Shiao CC, et al. Long-term risk of coronary events after AKI. J Am Soc Nephrol. 2014;25(3):595–605. https://doi.org/10.1681/ASN.2013060610.
13. Go AS, Hsu CY, Yang J, Tan TC, Zheng S, Ordonez JD, et al. Acute kidney Injury and Risk of Heart failure and atherosclerotic events. Clin J Am Soc Nephrol. 2018;13(6):833–41. https://doi.org/10.2215/CJN.12591117.
14. Guo CG, Zhao DB, Liu Q, Zhou ZX, Zhao P, Wang GQ, et al. A nomogram to predict lymph node metastasis in patients with early gastric cancer. Oncotarget. 2017;8(7):12203–10. https://doi.org/10.18632/oncotarget.14660.
15. Yang J, Li Y, Liu Q, Li L, Feng A, Wang T, et al. Brief introduction of medical database and data mining technology in big data era. J Evid Based Med. 2020;13(1):57–69. https://doi.org/10.1111/jebm.12373.
16. Johnson AE, Pollard TJ, Shen L, Lehman LW, Feng M, Ghassemi M, et al. MIMIC-III, a freely accessible critical care database. Sci Data. 2016;3:160035. https://doi.org/10.1038/sdata.2016.35.
17. von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP, et al. The strengthening the reporting of Observational studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Ann Intern Med. 2007;147(8):573–7. https://doi.org/10.7326/0003-4819-147-8-200710160-00010.
18. Yang YQ, Da JJ, Nie S, Yuan J, Liu BC, Liu HF, et al. A prediction model for moderate to severe acute kidney injury in people with heart failure. Mil Med Res. 2024;11(1):57. https://doi.org/10.1186/s40779-024-00558-z.
19. Banerjee D, Ali MA, Wang AY, Jha V. Acute kidney injury in acute heart failure-when to worry and when not to worry? Nephrol Dial Transpl. 2024;40(1):10–8. https://doi.org/10.1093/ndt/gfae146.
20. Redfield MM, Jacobsen SJ, Burnett JC Jr., Mahoney DW, Bailey KR, Rodeheffer RJ. Burden of systolic and diastolic ventricular dysfunction in the community: appreciating the scope of the heart failure epidemic. JAMA. 2003;289(2):194–202. https://doi.org/10.1001/jama.289.2.194.
21. Hogg K, Swedberg K, McMurray J. Heart failure with preserved left ventricular systolic function; epidemiology, clinical characteristics, and prognosis. J Am Coll Cardiol. 2004;43(3):317–27. https://doi.org/10.1016/j.jacc.2003.07.046.
22. Ratcliffe PJ. From erythropoietin to oxygen: hypoxia-inducible factor hydroxylases and the hypoxia signal pathway. Blood Purif. 2002;20(5):445–50. https://doi.org/10.1159/000065201.
23. Young JB, Abraham WT, Albert NM, Gattis Stough W, Gheorghiade M, Greenberg BH, et al. Relation of low hemoglobin and anemia to morbidity and mortality in patients hospitalized with heart failure (insight from the OPTIMIZE-HF registry). Am J Cardiol. 2008;101(2):223–30. https://doi.org/10.1016/j.amjcard.2007.07.067.
24. von Haehling S, Schefold JC, Hodoscek LM, Doehner W, Mannaa M, Anker SD, et al. Anaemia is an independent predictor of death in patients hospitalized for acute heart failure. Clin Res Cardiol. 2010;99(2):107–13. https://doi.org/10.1007/s00392-009-0092-3.
25. Wang Y, Xu X, Shi S, Gao X, Li Y, Wu H, et al. Blood urea nitrogen to creatinine ratio and long-term survival in patients with chronic heart failure. Eur J Med Res. 2023;28(1):343. https://doi.org/10.1186/s40001-023-01066-x.
26. Duan S, Li Y, Yang P. Predictive value of blood urea nitrogen in heart failure: a systematic review and meta-analysis. Front Cardiovasc Med. 2023;10:1189884. https://doi.org/10.3389/fcvm.2023.1189884.
27. Arora N. Serum chloride and heart failure. Kidney Med. 2023;5(4):100614doi. https://doi.org/10.1016/j.xkme.2023.100614.
28. De Bacquer D, De Backer G, De Buyzere M, Kornitzer M. Is low serum chloride level a risk factor for cardiovascular mortality? J Cardiovasc Risk. 1998;5(3):177–84.
29. Ettehad D, Emdin CA, Kiran A, Anderson SG, Callender T, Emberson J, et al. Blood pressure lowering for prevention of cardiovascular disease and death: a systematic review and meta-analysis. Lancet. 2016;387(10022):957–67. https://doi.org/10.1016/S0140-6736(15)01225-8.
30. Griffin BR, Vaughan-Sarrazin M, Shi Q, Ten Eyck P, Reisinger HS, Kennelty K, et al. Blood pressure, readmission, and Mortality among patients hospitalized with acute kidney Injury. JAMA Netw Open. 2024;7(5):e2410824. https://doi.org/10.1001/jamanetworkopen.2024.10824.
31. Han E, Prausmuller S, Weidenhammer A, Spinka G, Arfsten H, Bartko PE, et al. Renin trajectories and outcome in stable heart failure with reduced ejection fraction (HFrEF) on contemporary therapy: a Monocentric Study from an Austrian Tertiary Hospital Outpatient Clinic. J Renin Angiotensin Aldosterone Syst. 2023;2023:8883145. https://doi.org/10.1155/2023/8883145.

Publisher's note