ORIGINAL ARTICLE

Development of the Hemodynamic Instability Index in Acute Kidney Injury and its Association with In-Hospital Mortality

Desarrollo del Índice de Inestabilidad Hemodinámica en insuficiencia renal aguda y su asociación con la mortalidad hospitalaria

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ABSTRACT

Background: Hemodynamic instability increases the risk of in-hospital mortality in patients with acute kidney injury (AKI), but there is no specific tool to quantify this risk.
Objective: The aim of the present study was to develop the Hemodynamic Instability Index in Acute Kidney Injury (IIH-AKI), analyze its association with in-hospital mortality in patients hospitalized for AKI and compare its discriminatory ability with other established prognostic scores.
Methods: We conducted an analytical study based on a secondary database derived from a clinical record of 5060 patients hospitalized with AKI. The outcome analyzed was in-hospital mortality. Principal component analysis (PCA) was used to develop the HII-AKI model based on five key parameters: pulse, systolic blood pressure, diastolic blood pressure, respiratory rate, and oxygen saturation. The HII-AKI performance was evaluated using the area under the ROC curve (AUC-ROC), Kaplan-Meier curves, and Cox regression analysis.
Results: The HII-AKI prsented an AUC-ROC of 0.742 (95% CI 0.722-0.762; p<0.001) for predicting in-hospital mortality, surpassing the SOFA score (AUC-ROC=0.723) and the Elixhauser comorbidity index (AUC-ROC=0.465). Patients with high HII-AKI were younger and had a longer hospital stay. They also had more acidosis, lower bicarbonate levels, higher urea nitrogen levels, and lower creatinine levels. In Cox regression analysis, a high HII-AKI was associated with higher in-hospital mortality (HR=2.394; 95% CI 2.008-2.855; p<0.001).
Conclusion: A high HII-AKI is associated with greater hemodynamic instability, inflammation, metabolic disturbances, and prolonged length of hospital stay, supporting its usefulness as a prognostic marker of mortality in AKI. Its implementation in clinical practice could improve risk stratification and optimize the therapeutic decisions. Further studies are necessary for external validation.

Key words: Hemodynamic Monitoring - Acute Kidney Injury - In-Hospital Mortality - Survival Analysis - Disease Severity Index

RESUMEN

Introducción: La inestabilidad hemodinámica en la insuficiencia renal aguda (IRA) aumenta el riesgo de mortalidad hospitalaria, pero carece de una herramienta específica para cuantificarla.
Objetivo: Desarrollar el Índice de Inestabilidad Hemodinámica en Insuficiencia Renal Aguda (IIH-IRA), evaluar su asociación con la mortalidad intrahospitalaria y comparar su capacidad discriminativa frente a escalas pronósticas establecidas.
Material y métodos: Estudio analítico de datos secundarios de un registro clínico de 5060 pacientes hospitalizados con IRA. La variable de desenlace fue la mortalidad intrahospitalaria. Se aplicó análisis de componentes principales (ACP) para construir el IIH-IRA utilizando cinco parámetros clave: pulso, presión arterial sistólica, presión arterial diastólica, frecuencia respiratoria y saturación de oxígeno. Se evaluó su rendimiento con el análisis del área bajo la curva ROC (ABC ROC), curvas de Kaplan-Meier y regresión de Cox.
Resultados: El IIH-IRA mostró un ABC ROC de 0,742(IC95% 0,722-0,762;p<0,001) para predecir mortalidad hospitalaria, superando al índice SOFA (ABC ROC=0,723), y a la clasificación Elixhauser (ABC ROC=0,465). Los pacientes con IIH-IRA elevado fueron más jóvenes, con estadía hospitalaria más prolongada, más acidosis, bicarbonato más bajo, nitrógeno ureico más alto y creatinina más baja. En la regresión de Cox, un IIH-IRA elevado se asoció con mayor mortalidad hospitalaria (HR=2,394; IC95%:2,008 -2,855; p<0,001).
Conclusión: El IIH-IRA elevado se asocia con inestabilidad hemodinámica, inflamación, alteraciones metabólicas y mayor estadía hospitalaria. Ello respalda su utilidad como marcador pronóstico de mortalidad en IRA. Su aplicación podría mejorar la estratificación del riesgo y las decisiones terapéuticas.Se requieren más estudios para validar su uso externo.

Palabras clave: Monitorización Hemodinámica - Lesión Renal Aguda - Mortalidad Hospitalaria - Análisis de Supervivencia - Índice de Severidad de la Enfermedad

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INTRODUCTION

Acute kidney injury (AKI) is the sudden loss of renal function that causes retention of nitrogenous wastes and alterations in fluid, electrolyte, and acid–base balance. It can be differentiated into prerenal, intrarenal, and postrenal etiologies, which affect patients' outcomes. (1) Acute kidney injury is a predictor of poor prognosis in hospitalized patients, especially those in critical condition, where its association with hemodynamic instability increases the risk of multiple organ dysfunction and death. (2)

Hemodynamic instability in AKI is related to a decrease in effective intravascular volume, endothelial dysfunction, release of mediators of inflammation, and neurohormonal activation. These factors lead to tissue hypoperfusion, which perpetuates renal damage and affects other vital organs, producing a state of hemodynamic dysfunction condition is characterized by hypotension, tachycardia, and alterations in systemic vascular resistance. (3)

There are various tools for assessing the prognosis and mortality of hospitalized patients, such as the SOFA (Sequential Organ Failure Assessment) score and the Elixhauser Comorbidity Index. The SOFA score is a widely used metric in intensive care units to predict mortality based on multiple organ dysfunction. Its calculation is complex and requires the combination of numerous clinical and laboratory parameters. (4) Conversely, the Elixhauser Comorbidity Index enables the stratification of mortality risk based on patients' comorbidities. (5) However, these systems have not been specifically designed to assess hemodynamic instability in patients with AKI, which may limit their applicability in this population.

The assessment of hemodynamic instability in patients with AKI is essential to guide therapeutic interventions and stratify the risk of complications. However, there is currently no standardized index that quantifies hemodynamic instability and its association with in-hospital mortality, allowing for an objective assessment of the hemodynamic status of these patients.

The aim of the present study was to develop the Hemodynamic Instability Index in Acute Kidney Injury (HII-AKI) and analyze its association with in-hospital mortality in patients hospitalized for AKI. This novel index could allow for the early identification of patients at higher risk of death using less extensive clinical data than, for example, the SOFA score. Consequently, this will facilitate the optimization of clinical decisions and management strategies for this vulnerable population.

METHODS

Study design and population

We conducted an analytical study based on a secondary database derived from a clinical registry of patients hospitalized with AKI. (6) The original database included a total of 5,060 hospitalized adult patients; only those with complete information on in-hospital mortality were selected. Of these, 721 patients (14.2%) died during hospitalization, while 4339 (85.8%) survived. Acute kidney injury was defined according to the Kidney Disease: Improving Global Outcomes (KDIGO) criteria, which includes an increase in serum creatinine to 1.5 times or more than the baseline of the prior 7 days or an increase in serum creatinine by 0.3 mg/dL or more (26.5 μmol/L or more) within 48 hours. (7) This study was conducted in accordance with the RECORD (Reporting of Studies Conducted using Observational Routinely Collected Health Data) guideline, thereby ensuring transparency and methodological rigor in the management of routinely collected observational data.

Variables and measurements

The dependent variable was in-hospital mortality, defined as the death from any cause during hospitalization. This variable was recorded dichotomously (yes/no) and used as an outcome variable in the regression models to assess its association with the clinical and hemodynamic factors analyzed.

The independent variables used in this study were classified as continuous or categorical, depending on their nature and implementation in the different analyses. Continuous variables included clinical and hemodynamic parameters and laboratory test results. The following variables were analyzed: age (years), anion gap (mEq/L), serum bicarbonate (mEq/L), blood urea nitrogen (BUN, mg/dL), serum chloride (mEq/L), glomerular filtration rate (GFR, mL/min/1.73 m^2), creatinine levels on admission (mg/dL), hemoglobin (g/dL), platelet count ($\times 10^3/\mu$L), serum potassium (mEq/L), serum sodium (mEq/L), white blood cell count (WBC, $\times 10^3/\mu$L), systolic blood pressure (SBP, mmHg), diastolic blood pressure (DBP, mmHg), pulse (beats per minute), respiratory rate (breaths per minute), oxygen saturation (%), body temperature (°F), and length of hospital stay. These variables were analyzed using descriptive statistics and were used in the construction of indices and predictive models.

Categorical variables included the presence of previous diseases and clinical conditions. These included chronic kidney disease, heart failure, lung disease, diabetes, hypertension, cancer, and liver disease and recorded as dichotomous variables (present or absent). In addition, the Elixhauser Comorbidity Index and the SOFA score were considered and categorized into specific ranges to assess disease burden and organ dysfunction.

The principal component analysis (PCA) identified the variables that contributed most to the clinical variability of acute kidney injury. The principal component analysis (PCA) identified the variables that contributed most to the clinical variability of acute kidney injury. These included age, serum bicarbonate, BUN, serum chloride, GFR, hemoglobin, platelet count, serum potassium, serum sodium, WBC, SBP, DBP, pulse, respiratory rate, oxygen saturation, temperature, length of hospital stay, and creatinine levels at different times prior to hospitalization.

The Hemodynamic Instability Index in Acute Kidney Injury (HII-AKI) was constructed using five key variables: pulse, SBP, DBP, respiratory rate, and oxygen saturation. The index was then calculated using a specific formula, with an adjustment made to avoid negative values. Then, the clinical parameters were analyzed according to the HII-AKI and their association with in-hospital mortality using the Kaplan-Meier method and Cox regression analysis, which included variables such as HII-AKI, SOFA score, Elixhauser Comorbidity Index, creatinine level on admission, anion gap,

serum bicarbonate, BUN, serum chloride, GFR, hemoglobin, platelet count, serum potassium, serum sodium, WBC, and blood temperature. These variables were used in regression models to evaluate their association with in-hospital mortality and the relative risk of adverse events in patients with acute kidney injury.

The cohort included 51.5% of men (n = 2607) and 48.5% of women (n = 2453). Given the absence of statistically significant differences in in-hospital mortality based on sex ($p > 0.05$), this variable was not incorporated as a covariate in the multivariate models. However, it was maintained in the description of the study population for the purpose of reporting sex-disaggregated data.

Statistical analysis

Qualitative variables are presented as percentages and were compared using the chi-square test or Fisher's test, as appropriate. Quantitative variables are presented as mean and standard deviation (SD) or median and interquartile range (IQR), as appropriate and were compared using the t-test for normally distributed data and the Mann-Whitney U test for non-normal distributions.

To explore the internal structure of clinical and hemodynamic variables, principal component analysis (PCA) was applied. Sample adequacy was evaluated using the KMO test and Bartlett's sphericity test. Components with eigenvalues >1 were identified, and the five variables with the highest factor loadings (respiratory rate, oxygen saturation, pulse, systolic blood pressure, and diastolic blood pressure) were selected to construct the Hemodynamic Instability Index in Acute Kidney Injury (HII-AKI).

The discriminatory capacity of the HII-AKI to predict in-hospital mortality was evaluated by calculating the area under the ROC curve (AUC-ROC) and its 95% confidence interval (95% CI). This performance was compared with prognostic scales and relevant clinical parameters, including the SOFA score, Elixhauser Comorbidity Index, age, GFR, anion gap, serum creatinine, and white blood cell count, in order to determine the discriminatory capacity of the HII-AKI compared to conventional indicators.

The optimal cutoff point for HII-AKI was determined in 72.20 using the Youden index (J = sensitivity + specificity - 1), using the ROC curve for in-hospital mortality as a reference. Based on this value, patients were classified into two categories: low HII-AKI (<72.20) and high HII-AKI (≥72.20). Kaplan-Meier curves were constructed stratified by the cutoff point obtained (low vs. high HII-AKI) to analyze the association between the index and in-hospital survival. The curves were then compared using the log-rank test.

Finally, a Cox proportional hazards model was applied to estimate the hazard ratio (HR) of the HII-AKI, adjusted for clinical variables and significant prognostic scales (SOFA, Elixhauser, GFR, creatinine levels, anion gap, WBC). All the analyses were performed using a specialized statistical software package (SPSS 25), considering a level of significance of 0.05.

Ethical considerations

The secondary database was uploaded by the authors to Dryad, an open-access repository (https://datadryad.org/) under a Creative Commons (CC) license, allowing unrestricted use, distribution, and reuse of the data. To ensure the privacy of participants, the data were anonymized and numerically coded, in compliance with the ethical principles established in the Declaration of Helsinki for research on human subjects. (9) This process ensures that the database can be used in future research without compromising the confidentiality of the subjects. The information is available at the following link: https://datadryad.org/stash/dataset/doi:10.5061/dryad.kh189327p#citations.

RESULTS

A total of 5060 patients hospitalized for AKI were analyzed; mean age was 68.25 ± 15.50 years and the distribution by sex was balanced (51.5% were men and 48.50% were women). The patients exhibited the following metabolic and hemodynamic abnormalities: anion gap 12.01 ± 3.87 mEq/L, serum bicarbonate 23.42 ± 4.92 mEq/L, BUN 33.24 ± 19.39 mg/dL, GFR 63.49 ± 30.21 mL/min/1.73 m^2, and creatinine levels on admission 1.34 ± 0.72 mg/dL. Mean hemoglobin levels were 10.77 ± 2.43 g/dL, platelet count 227.33 ± 115.40 $\times 10^3/\mu L$, and WBC 11.32 ± 17.23 $\times 10^3/\mu L$. Mean systolic and diastolic blood pressure were 120.57 ± 22.25 mmHg and 67.74 ± 13.04 mmHg, respectively. The comorbidities recorded included chronic renal disease (25.4%), heart failure (31.8%), lung disease (30.4%), diabetes mellitus (37.5%), and hypertension (67.9%). The median SOFA score on admission was 2 points (IQR: 1–3) and the median length of hospital stay was 7 days (IQR: 4–13), reflecting a population with a high burden of comorbidities and physiological instability (Table 1)

Principal component analysis (PCA) identified seven pathophysiological components with eigenvalues > 1, which explained 62% of the total variance, with acceptable sample adequacy (KMO = 0.591; Bartlett $p < 0.001$). The first component encompassed renal function markers (creatinine, BUN, and GFR). The second component captured respiratory and acid–base parameters (respiratory rate, oxygen saturation, and bicarbonate). The third component represented hemodynamic measures (systolic and diastolic blood pressure, and pulse pressure). The remaining components reflected metabolic and hematological axes. Based on the factor loadings of the hemodynamic axis, the five variables with the greatest direct contribution to cardiovascular instability were selected—respiratory rate, oxygen saturation, pulse, systolic blood pressure, and diastolic blood pressure—and used to construct the Hemodynamic Instability Index in Acute Kidney Injury (HII-AKI) (Table 2)

PCA identified five key variables of hemodynamic instability in acute kidney injury: respiratory rate, oxygen saturation, pulse, systolic blood pressure, and diastolic blood pressure. These variables were weighted according to their factor loadings to construct the Acute Renal Failure Hemodynamic Instability Index (AKI-HII) formula. Pulse and respiratory rate had a positive contribution, while oxygen saturation and systolic and diastolic blood pressures had a negative influence. Before adjustment, HII-AKI values ranged from -129.21 to 22.49 (mean -60.81, standard deviation 19.22). To avoid negative values and facilitate clinical interpretation, 129.21 was added to all values.

Table 1. Clinical characteristics of the total population in the database of patients hospitalized for acute kidney injury (n = 5060)

Variable	
Age (years)	68.25 ± 15.50
Men (%)	51.50 (2607)
Women (%)	48.50 (2453)
Anion gap (mEq/L)	12.01 ± 3.87
Serum bicarbonate (mEq/L)	23.42 ± 4.92
BUN (mg/dL)	33.24 ± 19.39
GFR (mL/min/1.73 m²)	63.49 ± 30.21
Creatinine (mg/dL)	1.34 ± 0.72
Hemoglobin (g/dL)	10.77 ± 2.43
Platelet count (×10³/µL)	227.33 ± 115.40
White blood cells (×10³/µL)	11.32 ± 17.23
SBP (mmHg)	120.57 ± 22.25
DBP (mmHg)	67.74 ± 13.04
Chronic kidney disease (%)	25.4 (1285)
Heart failure (%)	31.80 (1607)
Lung disease (%)	30.40 (1539)
Diabetes mellitus (%)	37.50 (1898)
Hypertension (%)	67.90 (3438)
SOFA score	2 (1–3)
Length of hospital stay (days)	7 (4–13)

BUN: blood urea nitrogen; DBP: diastolic blood pressure; GFR: glomerular filtration rate; SBP: systolic blood pressure (mmHg); SOFA: Sequential Organ Failure Assessment.
Qualitative variables are presented as % (n) and quantitative variables as mean ± SD or median (IQR)

This adjustment resulted in an adjusted index with a range of 0 to 151.70, maintaining the same standard deviation, and with an adjusted mean of 68.39

The HII-AKI demonstrated effective performance in discriminating in-hospital mortality, with an AUC-ROC of 0.742 (95% CI 0.722 - 0.762; $p < 0.001$), surpassing the performance of other scales and biomarkers evaluated. The SOFA score exhibited an AUC-ROC of 0.723 (95% CI 0.702–0.744; $p < 0.001$), with a similar though slightly lower performance while the AUC-ROC of the Elixhauser Comorbidity Index was 0.465 (95% CI 0.442–0.489; $p = 0.003$), suggesting a limited discriminatory ability. Other clinical parameters, such as anion gap (AUC-ROC = 0.658), WBC count (AUC-ROC = 0.672), and age (AUC-ROC = 0.527) showed moderate to low performance. Oxygen saturation exhibited the lowest performance, with an AUC-ROC of 0.348 (95% CI 0.323–0.374; $p < 0.001$), indicating an inverse association with in-hospital mortality.

Patients with elevated HII-AKI (≥72.20) had significant differences in multiple clinical parameters. They were younger, and median length of hospital stay was longer [10 (IQR 5-19) days vs. 6 (IQR 4-12) days; $p < 0.001$]. These patients demonstrated elevated anion gap levels, reduced bicarbonate levels, and elevated BUN, findings that reflect greater severity of metabolic acidosis. In addition, hemoglobin concentration and blood pressure were significantly lower. Heart rate and respiratory rate were also higher, as well as white blood cell count. Oxygen saturation was reduced, reflecting significant cardiovascular and respiratory instability (Table 4)

Kaplan-Meier survival analysis showed significant differences in survival between patients with high HII-AKI (≥72.2) and those with a lower index. Median survival was significantly lower in the group with high HII-AKI (46.36 vs. 81.56 days). The log rank (Mantel-Cox) test demostrated a statistically significant difference between the two groups ($p < 0.001$). In the Cox regression analysis, HII-AKI emerged as the strongest predictor of in-hospital mortality, with a hazard ratio (HR) of 2.394 (95% CI 2.008 - 2.855). Compared to other severity scales, the SOFA score also showed a significant association with mortality (HR = 1.559; 95% CI 1.308 - 1.858), although the impact was lower than that of the HII-AKI. The Elixhauser Comorbidity Index did not demonstrate a significant association with mortality (Table 5).

DISCUSSION

This study employed principal component analysis (PCA) to identify the pathophysiological axes of AKI, with seven components explaining 62% of the total variance. These components reflect the dynamic interaction between renal function, acid-base balance, electrolytes, hemodynamics, metabolism, and age. The results, supported by an acceptable sample adequacy (KMO = 0.591) and a significant Bartlett's test ($p < 0.001$), showed that the first component grouped renal variables, creatinine levels, and BUN as the primary determinants. This finding is consistent with previous evidence that positions kidney dysfunction and the retention of nitrogenous wastes as independent predictors of hospital mortality, reflecting reduced glomerular filtration that contributes to systemic toxicity. (10,11) Furthermore, components associated with respiratory function and acid-base status were identified. These components influence tissue oxygenation and the risk of multiple organ dysfunction. (12, 13)

Based on this factor structure, five key variables associated with hemodynamic instability were identified: respiratory rate, oxygen saturation, pulse, SBP and DBP, which were used to construct the HII-AKI. The reduction in SBP and DBP, along with the compensatory increase in heart rate and respiratory rate, reflects a physiological response to hypoperfusion and circulatory compromise characteristic of AKI. In this context, the HII-AKI demonstrated a strong discriminatory ability to predict in-hospital mortality (AUC-ROC = 0.742), surpassing general scales such as the

Table 2. Principal component matrix of clinical variables and laboratory test results in acute kidney injury

Variable	C1	C2	C3	C4	C5	C6	C7
Age	0.295	-0.234	0.121	-0.370	0.200	0.518	-0.232
Serum bicarbonate	-0.293	-0.470	0.221	-0.336	0.573	-0.200	-0.063
BUN	0.708	0.086	-0.018	-0.121	0.223	0.170	-0.057
Serum chloride	0.081	0.218	0.823	0.134	-0.365	0.201	0.165
Glomerular filtration rate	-0.850	0.151	-0.095	0.077	-0.116	-0.080	0.049
Hemoglobin	-0.183	-0.207	-0.177	0.338	0.222	0.290	-0.258
Platelet count	-0.138	-0.072	-0.137	0.222	0.384	0.287	0.300
Serum potassium	0.263	0.186	-0.201	-0.069	-0.036	0.326	0.605
Serum sodium	0.018	0.131	0.866	0.108	-0.003	0.195	-0.173
White blood cells	0.011	0.244	-0.062	0.034	0.223	0.331	0.242
SBP	0.036	-0.494	0.208	0.568	0.129	0.020	0.052
DBP	-0.131	-0.421	0.047	0.750	0.069	-0.061	0.060
Pulse	-0.133	0.577	-0.035	0.334	0.153	-0.169	0.054
RR	0.027	0.465	0.000	0.160	0.345	0.172	-0.219
SpO_2	-0.007	-0.432	-0.166	0.060	-0.243	0.053	0.183
Temperature	-0.075	0.369	0.217	0.101	0.379	-0.294	0.172
Days of hospitalization	0.024	0.313	0.107	-0.067	0.289	-0.286	0.057
Creatinine on admission	0.901	-0.070	0.059	0.070	0.057	-0.126	0.045
Creatinine	0.909	0.007	-0.049	0.085	-0.002	-0.140	0.020
Min. creatinine 48 hours prior	0.944	-0.056	-0.018	0.077	0.007	-0.154	0.019
Min. creatinine 7 days prior	0.938	-0.086	0.004	0.083	0.005	-0.140	0.026
Anion gap	0.265	0.431	-0.405	0.362	-0.161	0.192	-0.431
AKI duration	0.002	-0.037	0.046	0.009	-0.086	-0.182	-0.201
KMO: 0.591; Bartlett's test: $\chi^2 = 68435.935$; $p < 0.001$; Explained variance: 62% (7 components)							

AKI: acute kidney injury; BUN: blood urea nitrogen; C: principal component; DBP: diastolic blood pressure; RR: respiratory rate; SaO_2: arterial oxygen saturation; SBP: systolic blood pressure

Table 3. Development of the HII-AKI

Variable	Load	Components in the HII-AKI formula
RR	0.46	0.465 × Respiratory rate
SaO_2	-0.432	(-0.432) × Oxygen saturation
Pulse	0.577	0.577 × Pulse
SBP	-0.494	(-0.494) × Systolic blood pressure
DBP	-0.421	(-0.421) × Diastolic blood pressure
HII-AKI formula		0.577 * Pulse + (- 0.494) * SBP + (- 0.421) * DBP + 0.465 * RR - 0.432 * SaO_2
Descriptive statistics of HII-AKI before adjustment		Minimum: -129.21, Maximum: 22.49, Mean: -60.81, SD: 19.22
Adjusted HII-AKI		HII-ARI+129.21
Descriptive statistics of HII-AKI after adjustment		Minimum: 0, Maximum: 151.70, Mean: 68.39, SD: 19.22

C: principal component; DBP: diastolic blood pressure; HII-AKI: Hemodynamic Instability Index in Acute Kidney Injury; RR: respiratory rate; SaO_2: arterial oxygen saturation; SBP: systolic blood pressure

Table 4. Clinical parameters according to the Hemodynamic Instability Index in Acute Kidney Injury (HII-AKI)

Parameter	Low HII-ARI (<72.2)	High HII-ARI (≥72.2)	p
Age (years)	69.46 ± 15.10	66.45 ± 15.89	<0.001
Length of hospital stay (days)	6 (4–12)	10 (5–19)	<0.001
Creatinine levels (mg/dL)	1.36 ± 0.71	1.28 ± 0.70	<0.001
Anion gap (mEq/L)	11.50 ± 3.30	12.79 ± 4.52	<0.001
Bicarbonate levels (mEq/L)	23.91 ± 4.42	22.67 ± 5.51	<0.001
BUN (mg/dL)	32.37 ± 18.74	34.54 ± 20.27	<0.001
Chloride levels (mEq/L)	102.25 ± 5.93	102.51 ± 6.63	0.147
GFR (mL/min/1.73 m²)	61.32 ± 29.56	66.99 ± 30.79	<0.001
Hemoglobin (g/dL)	11.02 ± 2.33	10.38 ± 2.52	<0.001
Platelet count (×10³/µL)	102	102	0.002
Potassium (mEq/L)	102	102	<0.001
Sodium (mEq/L)	102	102	0.043
WBC (×10³/µL)	102	102	<0.001
SBP (mmHg)	102	102	<0.001
DBP (mmHg)	102	102	<0.001
Pulse (bpm)	102	102	<0.001
Respiratory rate (rpm)	102	102	<0.001
Oxygen saturation (%)	102	102	<0.001

BUN: blood urea nitrogen; DBP: diastolic blood pressure (mmHg); GFR: glomerular filtration rate; HII-AKI: Index of Hemodynamic Instability in Acute Kidney Injury; SBP: systolic blood pressure (mmHg); WBC: white blood cells
Quantitative variables are presented as mean ± SD or median (IQR).

Table 5. Survival analysis

Variable	HR	95% CI	p
HII-AKI	2.394	2.008 - 2.855	<0.001
SOFA score	1,559	1,308 - 1,858	<0.001
Elixhauser comorbity index	1,154	0.904 - 1.474	0.251
Creatinine on admission	0.818	0.670 - 1.000	0.050
Anion gap	1.005	0.913 - 1.107	0.919
Bicarbonate	0.920	0.836 - 1.013	0.091
BUN	1.012	1.009 - 1.015	<0.001
Chloride	0.939	0.852 - 1.034	0.201
GFR	0.996	0.991 - 1.001	0.128
Hemoglobin	1.015	0.986 - 1.046	0.306
Platelet count	0.999	0.999 - 1.000	0.099
Potassium	1.268	1.126 - 1.428	<0.001
Sodium	1.094	0.992 - 1.206	0.072
WBC	1.002	1.001 - 1.004	<0.001

BUN: blood urea nitrogen; DBP: diastolic blood pressure (mmHg); GFR: glomerular filtration rate; HII-AKI: Index of Hemodynamic Instability in Acute Kidney Injury; SBP: systolic blood pressure (mmHg); WBC: white blood cells
Quantitative variables are presented as mean ± SD or median (IQR).

SOFA score or the Elixhauser Comorbidity Index, as well as isolated parameters such as the anion gap level or white blood cell count.

Compared to the SOFA score, the HII-AKI offers significant advantages, as it is based on basic, noninvasive, and easily reproducible hemodynamic monitoring parameters, making it particularly useful in resource-limited settings. While the SOFA score assesses multiple physiological systems, the IHII-AKI focuses on cardiovascular instability, a prognostic axis that is often underestimated for AKI progression. (14,15) This specificity explains its greater discriminatory power, suggesting that it could become a practical tool for risk stratification and therapeutic prioritization within general and critical care units.

Patients with elevated IHII-AKI (≥ 72.2) presented greater metabolic and inflammatory instability, elevated anion gap level, lower bicarbonate, higher BUN, and leukocytosis, along with clear signs of cardiovascular impairment: hypotension, tachycardia, tachypnea, and hypoxemia. They also had a longer length of hospital stay and a lower mean age, which could reflect more aggressive forms of hemodynamic dysfunction in young patients. These results are consistent with studies that have associated early circulatory instability with adverse outcomes and mortality in AKI. (16-18) By integrating these objective variables, the HII-AKI quantitatively synthesizes the impact of hemodynamic imbalance on prognosis, providing a clinical tool that can be immediately applied and validated in different healthcare settings.

Likewise, Kaplan–Meier survival analysis showed that patients with elevated HII-AKI had a lower probability of in-hospital survival, a difference that was statistically significant. In accordance with these findings, the Cox proportional hazards model revealed that a high HII-AKI was associated with an elevated risk of in-hospital mortality, even after adjusting for clinical variables and prognostic scales such as the SOFA score, the Elixhauser Comorbidity Index, and GFR, confirming the independent value of the tool as a prognostic predictor. This finding reinforces the role of the HII-AKI as a prognostic marker and suggests that acute cardiovascular impairment plays a central role in the progression and mortality associated with AKI, consistent with the mechanisms of systemic hypoperfusion and dysregulated inflammation described in recent literature. (19, 20)

The HII-AKI could have relevant implications for the clinical management of patients with acute kidney injury. By integrating simple hemodynamic parameters, this index could contribute to estimating the risk of in-hospital mortality and the early identification of patients with a higher probability of adverse outcomes. It could also facilitate more accurate risk stratification and guide monitoring or interventions according to individual clinical profiles. The use of this tool in intensive care units could help prioritize the allocation of resources to cases requiring close monitoring or adjustments in hemodynamic support. In addition, its prospective use could facilitate the evaluation of the clinical course and therapeutic response in real-time settings. Finally, the HII-AKI has the potential to serve as a valuable research instrument in examining the association between hemodynamic instability and clinical outcomes in acute kidney injury. However, external validation is necessary before its implementation in routine clinical practice.

Among the limitations of this study, despite the amount of data available, the retrospective analysis of a hospital cohort could restrict the generalizability of the findings to other settings. Additionally, while PCA enabled the identification of key pathophysiological axes, the selection of variables and the methodology may influence the interpretation of results. Further research is necessary to externally validate the HII-AKI and explore its usefulness for the early management of AKI.

In conclusion, a high HII-AKI is associated with greater hemodynamic instability, inflammation, metabolic disturbances, and prolonged length of hospital stay, supporting its usefulness as a prognostic marker. This index represents an innovative tool for assessing hemodynamic instability in AKI, with a discriminatory ability superior to other scores and biomarkers. Its implementation in clinical practice could improve risk stratification and optimize the therapeutic management of this vulnerable population. It is imperative to conduct further research in diverse cohorts to evaluate the generalizability of these findings.

Conflicts of interest

None declared.

(See authors' conflict of interests forms on the web).

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