

# Renal Resistive Index is Associated With Acute Kidney Injury in COVID-19 Patients Treated in the ICU

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## Research

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# Abstract

**Background:** Renal resistive index (RRI) is a promising tool for prediction of acute kidney injury (AKI) in critically ill patients but is not described among patients with Coronavirus disease 2019 (COVID-19). The aim of this study was to describe the pattern of RRI in relation to AKI in patients with COVID-19 treated in the intensive care unit.

**Methods:** In this observational cohort study, RRI was measured in COVID-19 patients in six ICUs at two sites of a Swedish University Hospital. AKI was defined by the creatinine criteria in the Kidney Disease Improving Global Outcome classification. We investigated the association between RRI and AKI diagnosis, different AKI stages and urine output.

**Results:** RRI was measured in 51 patients, of which 23 patients (45%) had AKI at the time of measurement. Median RRI in patients with AKI was 0.80 (IQR 0.71-0.85) compared to 0.72 (IQR 0.67-0.78) in patients without AKI ( $p=0.004$ ). Compared to patients without AKI, RRI was higher in patients with AKI stage 3 (median 0.83, IQR 0.71-0.85,  $p=0.006$ ) but not in patients with AKI stage 1 (median 0.76, IQR 0.71-0.83,  $p=0.347$ ) or AKI stage 2 (median 0.79, min/max 0.79/0.80,  $n=2$ ,  $p=0.134$ ). RRI was higher in patients with an ongoing AKI episode compared to patients who never developed AKI (median 0.72, IQR 0.69-0.78,  $p=0.015$ ) or patients who developed AKI but had recovered at the time of measurement (median 0.68, IQR 0.67-0.81,  $p=0.021$ ). Oliguric patients had higher RRI (median 0.84, IQR 0.83-0.85) compared to non-oliguric patients (median 0.74, IQR 0.69-0.81) ( $p=0.009$ ).

**Conclusions:** Critically ill COVID-19 patients with AKI have higher RRI compared to those without AKI, and elevated RRI may have a role in identifying severe and oliguric AKI in these patients.

## Background

The Coronavirus disease 2019 (COVID-19) pandemic is causing great suffering and is placing strain on health care systems worldwide. Acute kidney injury (AKI) is a common complication in critically ill patients with COVID-19. Initial studies have reported incidences from 20 up to almost 90% among patients admitted to the intensive care unit (ICU) or in need of mechanical ventilation [1–4], of which up to one third have been treated with renal replacement therapy (RRT) [5, 6].

Among patients with COVID-19 the risk of death may be increased 13-fold in those who develop AKI compared to those who do not [4, 7, 8]. The pathophysiological mechanisms giving rise to AKI in COVID-19 are not fully understood, and diagnostic tools for quick and reliable identification of the renal injury are needed.

Renal resistive index (RRI) is an ultrasonographic Doppler-measurement of flow velocities in intraparenchymal renal arteries. Normal values are around 0.60 [9, 10] with 0.70 considered the upper normal threshold in adults [11]. Elevated RRI has shown promise in early detection and prognostication of AKI in mixed ICU populations [12–16], and the method seems feasible within the scope of point-of-care

ultrasonography (POCUS) [17]. The role of RRI to guide diagnosis and treatment of AKI in COVID-19 patients is unknown. The aim of this study was to describe the pattern of RRI in relation to AKI in patients with COVID-19 treated in the ICU. We specifically investigated if there was an association between RRI and AKI diagnosis, different AKI stages and urine output.

## Methods

### Study population

This was an observational cohort study conducted in six ICUs designated for COVID-19 patients (COVID-ICUs) at a Swedish University Hospital. Four ICUs were at one of two sites, and two at the other site. On specific days when sonographers were available, patients in each COVID-ICU were screened for participation. Inclusion criteria were infection with Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) detected by a positive reverse transcriptase-polymerase chain reaction taken from upper or lower airways, admission to a COVID-ICU, and age  $\geq 18$  years. Exclusion criteria were ongoing extracorporeal membrane oxygenation (ECMO).

The study complied with the Declaration of Helsinki and was approved by the Swedish Ethical Review Authority. Requirement for signed informed consent was waived. A printed information sheet was sent to each patient or next of kin with the opportunity to retrospectively withdraw participation.

### Definitions

AKI was defined according to the Kidney Disease Improving Global Outcome (KDIGO) classification as an increase in serum creatinine concentration (sCr) and categorized into three stages [18]. The highest sCr from ICU admission to the day of RRI measurement was compared to baseline sCr. Baseline sCr was defined as the last known value measured in a disease-free phase before admission. When no previous sCr value existed, hospital admission sCr was used. The AKI stages were defined as the following: stage 1,  $\geq 1.5$ - to 1.9-fold increase or an absolute increase  $\geq 26 \mu\text{mol/l}$ ; stage 2,  $\geq 2.0$ - to 2.9-fold increase; stage 3,  $\geq 3.0$ -fold increase or an absolute increase  $> 354 \mu\text{mol/l}$  or initiation of RRT. The KDIGO urine output criteria was not used since hourly urine output was not always registered in the medical records. If the sCr elevation occurred more than seven days before the RRI measurement and its value had returned to  $< 1.5$ -fold or  $< 26 \mu\text{mol/l}$  higher than from baseline, the patient was evaluated as having recovered from an AKI episode and was classified into the no AKI group. Oliguria at the time of RRI measurement was defined as urine output  $< 0.5 \text{ ml/kg ideal body weight/hour}$  for 24 hours regardless of diuretic drug administration [19]. Ideal body weight was calculated using the gender-specific Acute Respiratory Distress Syndrome Network formula [20]. Chronic kidney disease (CKD) was defined as estimated glomerular filtration rate (eGFR)  $< 60 \text{ mL/min/1.73 m}^2$ , and eGFR was calculated using the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) equation [21]. For this, baseline sCr was used when classifying patients as having CKD and a combination of sCr and cystatin C was used when calculating eGFR at the time of RRI measurement. Comorbidities were considered present if documented in the patient's medical record or if the patient was prescribed medication for the current state. The

cardiovascular disease group included patients with cardiac failure, atrial arrhythmia, prior myocardial infarction or prior cardiac surgery.

## **RRI measurements**

All RRI measurements were performed by one of two operators (MR and OJ). Both operators had more than one year's clinical experience of the RRI method. For each site a designated ultrasound device with a curvilinear probe of 1.0–6.0 MHz was used (GE Vivid S70N, US and GE Logiq E10, US at the two sites respectively). The patients were examined in their ICU bed in supine or prone position depending on their respiratory requirements. Both kidneys were examined, and measurements were made on both or the most accessible side since the difference in RRI values between the right and left kidney has been shown to be negligible both in healthy and critically ill patients [9, 12, 17]. After obtaining a complete view of the kidney, color-Doppler was applied to visualize the global organization of intrarenal blood vessels. Pulse waved Doppler at the smallest possible width between 2–5 mm was used to measure flow velocities in an interlobular- or arcuate artery in the upper, middle and lower kidney pole. The Doppler gain was set to obtain a clear outline of flow waves with minimal background noise. The Pulse waved Doppler spectrum was considered optimal when at least three consecutive similar-looking waveforms for each pole were visualized. RRI was calculated for each pole as  $[(\text{peak systolic velocity} - \text{end-diastolic velocity}) / \text{peak systolic velocity}]$ . From the pole RRI values, a mean RRI was computed.

## **Data collection**

The following clinical data were collected for each patient at the time of RRI measurement; hemodynamic parameters, vasopressor requirements, sedatives dose and ventilator settings if mechanically ventilated. Severity of illness was graded on the day of measurement using the Sequential Organ Failure Assessment (SOFA) (originally the Sepsis-related Organ Failure Assessment) score [22]. Information on comorbidities, regular and current medication and laboratory data were collected from medical records.

## **Statistical analysis**

Patient characteristics and variables are presented using frequencies and percentages for categorical data, and medians with interquartile range (IQR) and minimum/maximum (min/max) values for continuous data. Clinical characteristics of patients with or without AKI were compared using Fischer's exact test for dichotomous variables and Wilcoxon rank-sum test for continuous variables. Median RRI between different groups were compared using the Wilcoxon rank-sum test. A p-value < 0.05 was considered significant. The following variables had missing data: hospital admission sCr (n = 7 [14%]) and urine output at the day of RRI measurement (n = 2 [4%]). Missing data on height (n = 1 [2%]) was substituted with the median value according to sex. Statistical analyses were performed using Stata version 15.1 (StataCorp, College Station, US).

## **Results**

Between April 15 and May 15 in 2020, the six COVID-ICUs were screened. In four of the ICUs all patients treated on the wards on a specific date were screened. In the remaining two ICUs patients were screened on several dates due to logistical reasons, and a convenience sample of patients was made when at least one of the operators was available and able to perform measurements on an accessible patient. Out of 71 screened patients, 20 were excluded, and a total of 51 patients were analyzed (Fig. 1).

Patient characteristics of the study population are presented in Table 1. Median age was 63 (IQR 57–67, min/max 29/74) and 88% were male. At the time of RRI measurement 23 patients (45%) had AKI (stage 1, n = 4 (8%); stage 2, n = 2 (4%); stage 3, n = 17 (33%) with n = 13 (25%) treated with continuous RRT [CRRT]). Among the 28 patients (55%) who did not have AKI, 11 patients (22%) previously during the ICU course had an AKI episode but had recovered (recovered from stage 1, n = 7 (14%); from stage 2, n = 2 (4%); from stage 3, n = 2 [4%]) and 17 patients (33%) never had AKI. Compared to patients without AKI, the AKI patients had a higher body mass index and a lower incidence of cardiovascular disease. At the time of RRI measurement, AKI patients had a higher SOFA-score, a higher incidence of mechanical ventilation and vasopressor use, lower eGFR and were more often oliguric compared to patients without AKI. From ICU-admission to the day of RRI measurement patients in the AKI group presented with higher maximum concentrations of C-reactive protein, white blood cell count, procalcitonin, D-dimer and fibrinogen.

Table 1  
Patient characteristics of all patients and those with and without AKI.

	<b>All patients (n = 51)</b>	<b>No AKI (n = 28)</b>	<b>AKI (n = 23)</b>	<b>P-value no AKI vs AKI</b>
<b>Age</b> , median (IQR)	63 (57–67)	63 (58–68)	64 (53–65)	0.48
<b>Sex</b> , n (%)				0.027
Male	45 (88)	22 (79)	23 (100)	
Female	6 (12)	6 (21)	0 (0)	
<b>BMI</b> , median (IQR)	28.7 (25.2–31.2)	26.8 (24.6–29.9)	30.9 (27.0–34.7)	0.012
<b>Risk factors for AKI</b> , n (%)				
Hypertension	29 (57)	15 (54)	14 (61)	0.78
Diabetes	10 (20)	5 (18)	5 (22)	0.74
Chronic lung disease	11 (22)	7 (25)	4 (17)	0.73
Cardiovascular disease	6 (12)	6 (21)	0 (0)	0.027
Chronic kidney disease <sup>a,b</sup>	6 (12)	1 (4)	5 (22)	0.079
No risk factor <sup>c</sup>	15 (29)	7 (25)	8 (35)	0.54
<b>Data at RRI measurement</b>				
ICU-day, median (IQR)	18 (6–29)	16 (6–26)	19 (10–31)	0.19
SOFA-score, median (IQR)	5 (4–8)	4 (3–7)	7 (5–10)	0.003
Mechanical ventilation, n (%)	38 (75)	17 (61)	21 (91)	0.022
Prone position, n (%)	9 (18)	5 (18)	4 (17)	1.00
Vasopressors, n (%)	26 (51)	10 (36)	16 (70)	0.025
eGFR <sup>b</sup> , median (IQR)	58 (41–75)	70 (52–80)	26 (13–41)	< 0.001
Oliguria <sup>d</sup> , n (%)	5 (24)	0 (0)	5 (24)	0.011
RRT, n (%)				
Continuous RRT	13 (25)	0 (0)	13 (57)	< 0.001
Intermittent HD	0 (0)			
<b>Treatment in ICU<sup>e</sup></b> , n (%)				

	<b>All patients (n = 51)</b>	<b>No AKI (n = 28)</b>	<b>AKI (n = 23)</b>	<b>P-value no AKI vs AKI</b>
Mechanical ventilation	49 (96)	26 (93)	23 (100)	0.49
Vasopressors	49 (96)	26 (93)	23 (100)	0.49
RRT				
Continuous RRT	13 (25)	0 (0)	13 (57)	< 0.001
Intermittent HD	1 (2)	0 (0)	1 (4)	0.45
Diuretics	48 (94)	25 (89)	23 (100)	0.24
Anti-inflammatory drugs				
Corticosteroids	37 (73)	21 (75)	16 (70)	0.76
Tocilizumab	3 (6)	3 (11)	0 (0)	0.24
Antiviral drugs				
Chloroquin	1 (2)	0 (0)	1 (4)	0.45
Remdesivir	2 (4)	2 (7)	0 (0)	0.49
Anticoagulation drugs				
LMWH	51 (100)	28 (100)	23 (100)	
Antiplatelets	33 (65)	21 (75)	12 (52)	0.14
Episode of thrombolysis	4 (8)	1 (4)	3 (13)	0.32
<b>Laboratory values<sup>f</sup>, median (IQR)</b>				
C-reactive protein, mg/L	361 (316–433)	327 (254–382)	418 (358–485)	< 0.001
White blood cell count, 10 <sup>9</sup> /L	20.3 (15.7–28.1)	18.4 (13.3–21.9)	25.2 (19.4–32.7)	0.009
Procalcitonin, µg/L	4.9 (1.2–15.0)	2.0 (0.9–11.2)	9.8 (3.5–18.0)	0.009
Interleukin-6, ng/L	454 (176–1211)	380 (168–1186)	478 (274–1231)	0.74

	All patients (n = 51)	No AKI (n = 28)	AKI (n = 23)	P-value no AKI vs AKI
Ferritin, µg/L	2547 (1742–4352)	2313 (1635–4230)	2606 (2048–4352)	0.48
D-dimer, mg/L FEU	10.0 (4.8–32.4)	8.3 (3.8–14.6)	13.7 (7.1–35.0)	0.021
Fibrinogen, g/L	8.8 (7.8– 11.7)	8.6 (7.1–9.5)	9.5 (8.1–12.0)	0.032
HScTnT, ng/L	89 (33–184)	73 (23–159)	134 (34–211)	0.16
<p>Abbreviations: AKI, acute kidney injury; BMI, body mass index (kg/m<sup>2</sup>); RRI, renal resistive index; ICU, intensive care unit; SOFA-score, sequential organ failure assessment score; eGFR, estimated glomerular filtration rate (ml/min/1.73 m<sup>2</sup>); RRT, renal replacement therapy; HD, hemodialysis; LMWH, low-molecular-weight heparin; FEU, fibrinogen equivalent units; HScTnT, highly sensitivity cardiac troponin T.</p> <p><sup>a</sup> Chronic kidney disease was defined as eGFR before ICU admission &lt; 60 ml/min/1.73 m<sup>2</sup></p> <p><sup>b</sup> eGFR was calculated using the CKD-EPI equation using serum creatinine for classification of chronic kidney disease, and a combination of serum creatinine and cystatin C at the time of RRI measurement</p> <p><sup>c</sup> Patients without history of smoking, chronic diagnoses or regular medications at hospital admission</p> <p><sup>d</sup> Oliguria was defined as urine output &lt; 0.5 ml/kg ideal body weight/hour for 24 hours</p> <p><sup>e</sup> Treatment from ICU-admission to RRI measurement</p> <p><sup>f</sup> Maximum laboratory values from ICU-admission to RRI measurement</p>				

RRI was measured most often in the third week of the ICU- and hospital course (median ICU day 18, IQR 6–29, min/max 0/37; median hospital day 20, IQR 10–30, min/max 2/37) and four weeks from symptom debut of COVID-19 (median 28, IQR 22–40, min/max 7/72). In 27 patients (53%) RRI was calculated from measurements in the right kidney, in 12 patients (23,5%) from measurements in the left kidney and in 12 patients (23,5%) from measurements in both kidneys. Forty-two patients (82%) were examined in supine- and nine patients (18%) in prone position.

## RRI in relation to AKI and AKI stage

Median RRI in the study population was 0.76 (IQR 0.69–0.82, min/max 0.62/1.0). One patient had completely diminished end-diastolic blood flow resulting in an RRI of 1.0. Median RRI in patients with AKI was 0.80 (IQR 0.71–0.85, min/max 0.66/1.0) compared to 0.72 (IQR 0.67–0.78, min/max 0.62/0.84) in patients without AKI (p = 0.004) (Fig. 2). There was no difference in RRI between AKI stage 1 (median

0.76, IQR 0.71–0.83, min/max 0.67/0.88) or AKI stage 2 (median 0.79, min/max 0.79/0.80, n = 2) compared to no AKI (p = 0.347 and 0.134 respectively), but RRI was higher in patients with AKI stage 3 (median 0.83, IQR 0.71–0.85, min/max 0.66/1.0) compared to patients without AKI (p = 0.006) (Fig. 2).

## RRI in relation to non-AKI, recovered AKI and ongoing AKI

RRI did not differ within the no AKI group when comparing patients who never had AKI (median 0.72, IQR 0.69–0.78, min/max 0.62/0.83) to patients with recovered AKI (median 0.68, IQR 0.67–0.81, min/max 0.65/0.84) (p = 0.621), but RRI was higher in the AKI group compared to both these groups (p = 0.015 and 0.021 respectively) (Fig. 3).

## RRI in relation to oliguria

RRI was higher in oliguric patients (median 0.84, IQR 0.83–0.85, min/max 0.80/0.97) compared to non-oliguric patients (median 0.74, IQR 0.69–0.81, min/max 0.62/1.0) (p = 0.009) (Fig. 4).

## Discussion

This is the first study to describe RRI in patients with COVID-19. RRI was higher in patients with AKI compared to patients without AKI. RRI could distinguish patients with severe AKI from patients without AKI, and was higher in patients with an ongoing AKI episode compared to patients who had recovered from AKI earlier during the ICU course. Oliguric patients had higher RRI compared to non-oliguric patients.

Our results are in line with previous studies on mixed- or septic ICU patients, where RRI has been shown to be able to distinguish severe or persistent AKI from no or transient AKI [12, 13, 16, 23, 24]. In these studies, optimal RRI cut-off values for this discrimination have varied from 0.69 to 0.80. The median RRI of 0.80 in patients with AKI in our population must be considered high in comparison but may partly be due to the large proportion of patients with AKI stage 3 at the time of RRI measurement. Notably, patients without AKI in our study had higher RRI (median 0.72) compared to non-AKI patients in ICU populations without COVID-19 where reported values typically are lower than 0.65 [12, 14, 25]. It is not clear if elevated RRI in patients without AKI but infected with SARS-CoV-2 is a result of the infection itself, or if it reflects severity of illness as indicated by the long length of ICU stay as well as the high incidence of mechanical ventilation and vasopressor use in our population.

Proposed pathophysiological mechanisms of AKI in COVID-19 include hyperinflammation, altered regulation of the Renin-Angiotensin-Aldosterone-system with vasoconstriction and endothelial activation, hypercoagulability with development of microthrombi, and direct infection and damage of tubular cells and podocytes by SARS-CoV-2 via angiotensin-converting enzyme 2 receptors [2, 26, 27]. In ICU patients, unspecific kidney injury mechanisms such as hypo- or hypervolemia, use of nephrotoxic agents and hemodynamic changes due to mechanical ventilation with high levels of positive end expiratory pressures add to this burden [2]. Several renal and extrarenal factors influence the RRI value, and in complex clinical settings the final profile of the flow wave and RRI are difficult to predict [28]. The

hypothesis that thrombi in the renal microcirculation may be a pathophysiological mechanism contributing to AKI in COVID-19 is supported by reports of high rates of thrombotic complications in hospitalized COVID-19 patients [29–31]. Both patients with and without AKI in our study presented with laboratory markers of hyperinflammation and deranged coagulation, but whether renal microthrombi contributed to the generally high RRI values observed in our population is unclear and needs further exploration.

Previous studies have in general focused on prediction of AKI from RRI measurements performed within the first day of ICU admission [12, 14–16, 23]. However, the ability of early RRI measurements to predict short-term AKI reversibility within three days recently has been challenged [32, 33]. Our finding of higher RRI in patients with an ongoing AKI episode compared to patients who had recovered from an AKI episode earlier during the ICU course suggests that RRI values rapidly decrease with recovered renal function. This indicates that RRI also might have a role later in the ICU- or hospital course for prediction of long-term renal recovery or progression towards CKD.

In our population of COVID-19 patients there was a strong association between elevated RRI and oliguria, and all oliguric patients had RRI values  $\geq 0.80$ . One possible explanation could be oedema and increased pressure within the renal capsule. Elevated RRI values have been reported in animal models of increased renal interstitial pressure [34], and recently the venous impedance index calculated from measurements of intrarenal venous flow velocities have been investigated in ICU patients to assess the role of fluid overload on AKI [33]. The fact that all oliguric patients in our population presented with very high RRI values suggests that RRI may have a role in the prediction of successful weaning from CRRT. A high incidence of circuit clotting has been described in COVID-19 patients on CRRT [29], and an RRI  $\geq 0.80$  in such a situation may indicate that restarting dialysis will be necessary while a lower value instead might suggest that pharmacological diuresis is appropriate.

As a non-invasive and repeatable bedside method, RRI is an interesting tool for the assessment of AKI in critically ill patients with COVID-19. The method has been demonstrated in different settings and centers to be easy and fast to learn even for non-experienced sonographers [17, 35], and should be applicable within POCUS-protocols for ICU clinicians even in the present resource scarce times of a pandemic.

Our study has several limitations. First, our study population was small, partly due to the fact that we used a convenience sample in two of the six COVID-ICUs. However, the included patients were severely ill with a large proportion having AKI, meaning the number of patients with AKI was in line with many previous RRI studies on ICU populations [15, 24, 35]. Second, RRI measurements were performed at different time points in different patients, and most of the measurements were made late in the ICU course. During the peak of the pandemic in Sweden, the involved University Hospital functioned as a referral hospital and many patients were transferred to its ICUs from other hospitals when they already had received several days of intensive care. This meant there was a delay from ICU admission to accessibility in some of the patients. However, it also meant that most of the measurements were performed in a hemodynamically stable phase reducing the influence of hemodynamic factors on the RRI

value as well as allowing the comparison of RRI in patients with or without recovered AKI episodes. Third, intra- and interobserver variability for the operators were not investigated. Our group has previously shown that RRI measurements by inexperienced sonographers were reliable, accurate and precise compared to an expert after only a brief training session [17], and both operators in our study were experienced with the RRI method. Lastly, our study was affected by some of the well-known pitfalls in AKI-research. The use of hospital admission sCr as baseline level in patients in whom pre-admission sCr was missing might have resulted in an underestimation of the AKI-incidence. Further, using sCr decline to define recovery from an AKI episode could in patients with muscle wasting during a prolonged ICU course lead to overestimation of renal function recovery [36]. However, we used eGFR-calculations based on a combination of sCr and cystatin C at the time of RRI measurement and still observed a difference in estimated renal function between patients classified with or without AKI, suggesting any such misclassification was negligible.

## Conclusion

Critically ill COVID-19 patients with AKI have higher RRI compared to those without AKI, and elevated RRI may have a role in identifying severe and oliguric AKI in these patients. The exact role of RRI in AKI prediction and prognostication in ICU patients with COVID-19 should be established in further studies.

## Abbreviations

COVID-19

Coronavirus disease 2019

AKI

Acute kidney injury

ICU

Intensive care unit

RRT

Renal replacement therapy

RRI

Renal resistive index

POCUS

Point-of-care ultrasonography

COVID-ICU

Intensive care unit designated for care of COVID-19 patients

SARS-CoV-2

Severe Acute Respiratory Syndrome Coronavirus 2

ECMO

Extracorporeal membrane oxygenation

KDIGO

Kidney Disease Improving Global Outcome  
sCr  
Serum creatinine concentration  
eGFR  
Estimated glomerular filtration rate  
CKD-EPI  
Chronic Kidney Disease Epidemiology Collaboration  
CKD  
Chronic kidney disease  
BMI  
Body mass index  
SOFA  
Sequential Organ Failure Assessment  
IQR  
Interquartile range  
min/max  
Minimum/maximum  
CRRT  
Continuous renal replacement therapy

## **Declarations**

## **Ethics approval and consent to participate:**

The current study was approved by the Swedish Ethical Review Authority (registration number 202100-6925). The need for signed informed consent was waived. A printed information sheet was sent to each patient or next of kin with the opportunity to retrospectively withdraw participation.

### **Consent for publication:**

Written informed consent for publication of the ultrasound image in the graphical abstract was obtained from the volunteer that was examined. A copy of the consent form is available for review by the Editor of this journal.

### **Availability of data and material:**

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

### **Competing interests:**

The authors declare that they have no competing interests.

## Funding:

This research received no specific funding.

## Authors' contributions:

MR, DH, MB, and CRS conceived the study. MR, OJ and NK performed the data collection. MR and DH conducted the analyses and interpretation of the data. MR drafted the manuscript. DH, MB, CRS, OJ and NK substantially revised the manuscript. DH and MB supervised the process. All authors read and approved the final manuscript.

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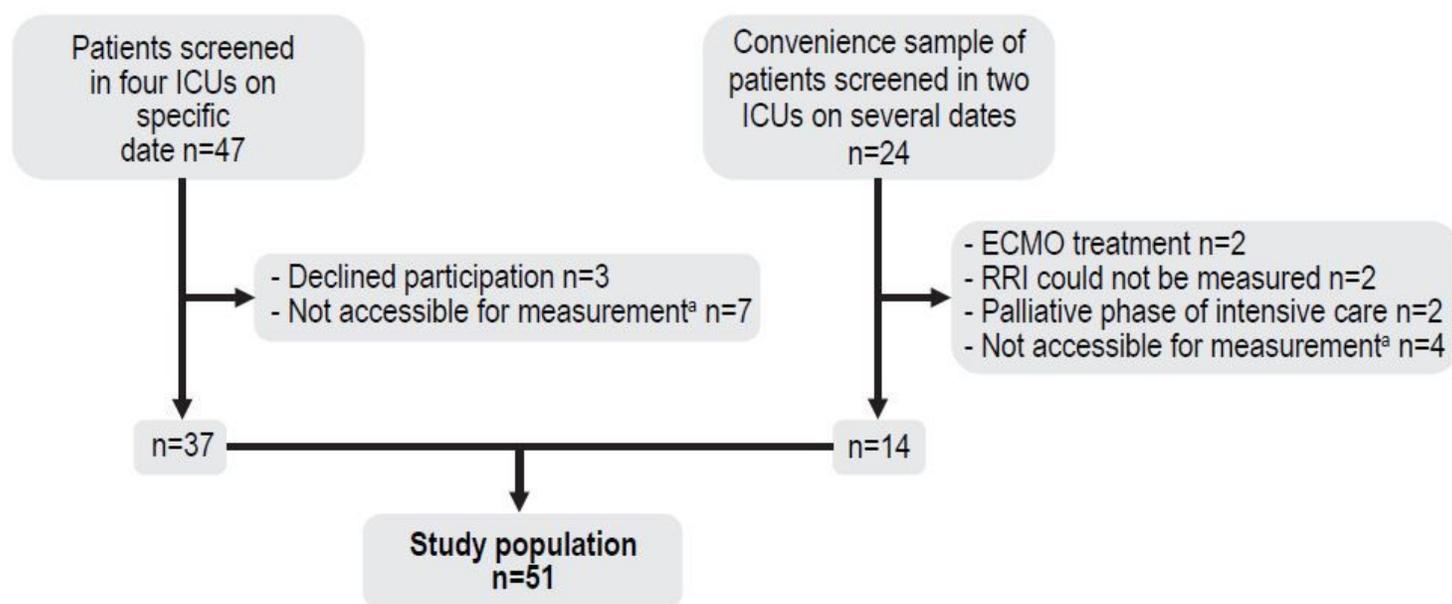
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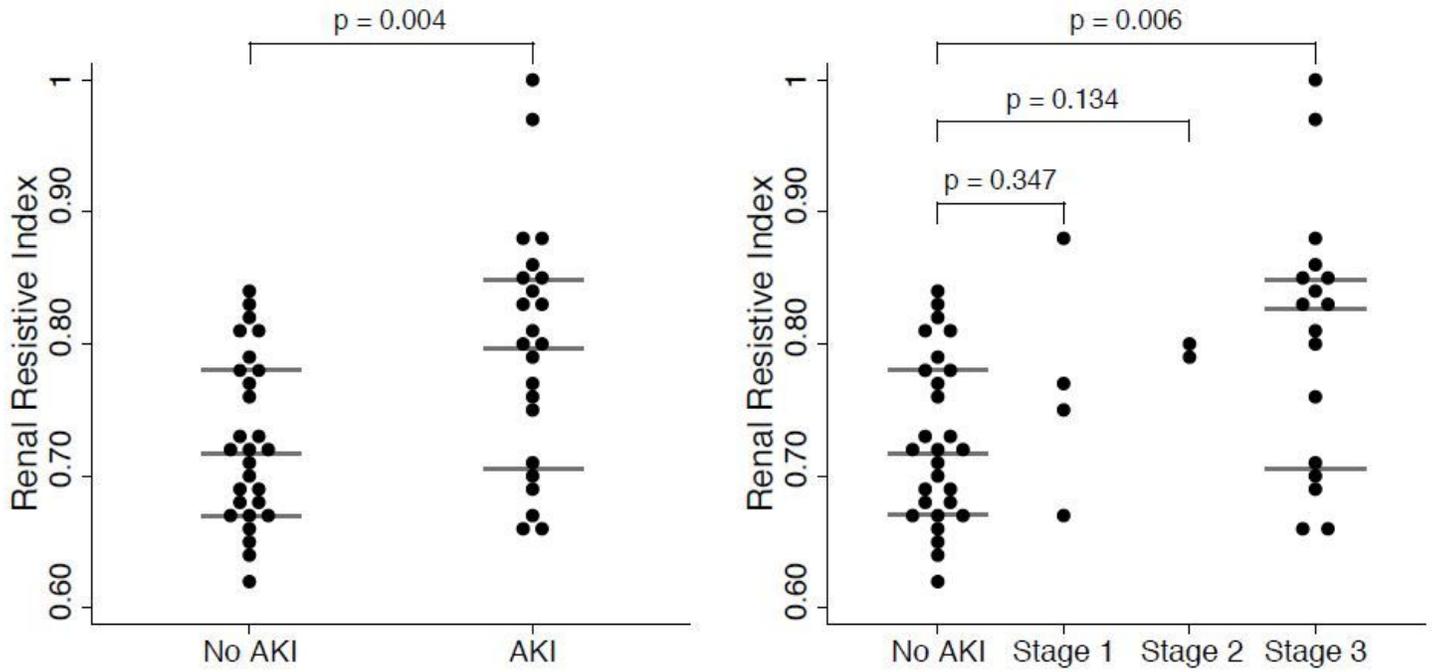
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## Figures



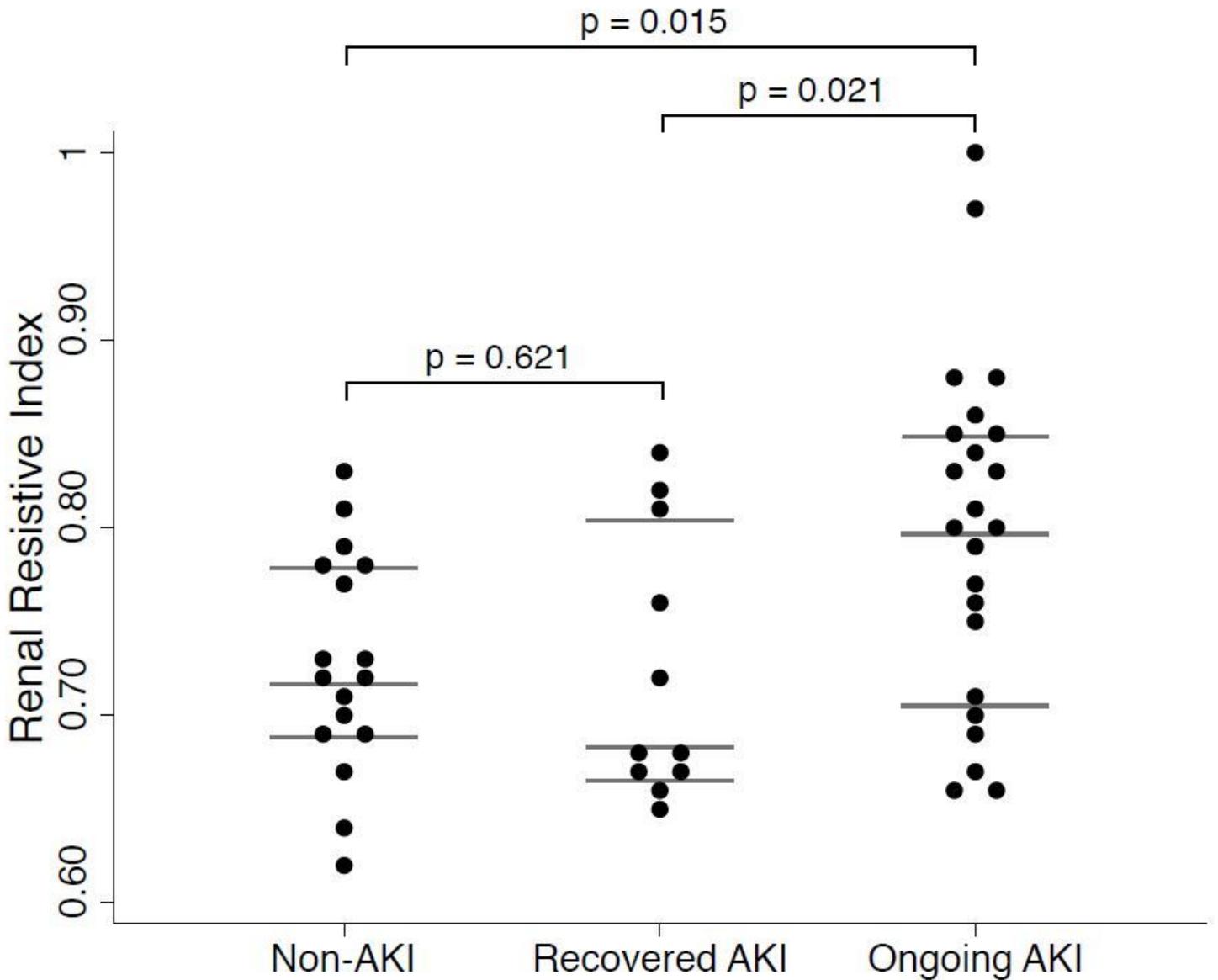
**Figure 1**

Selection of the study population. a Not accessible due to delirium/agitation, ongoing resuscitation, ongoing long period of mobilization/physiotherapy or unknown reason.



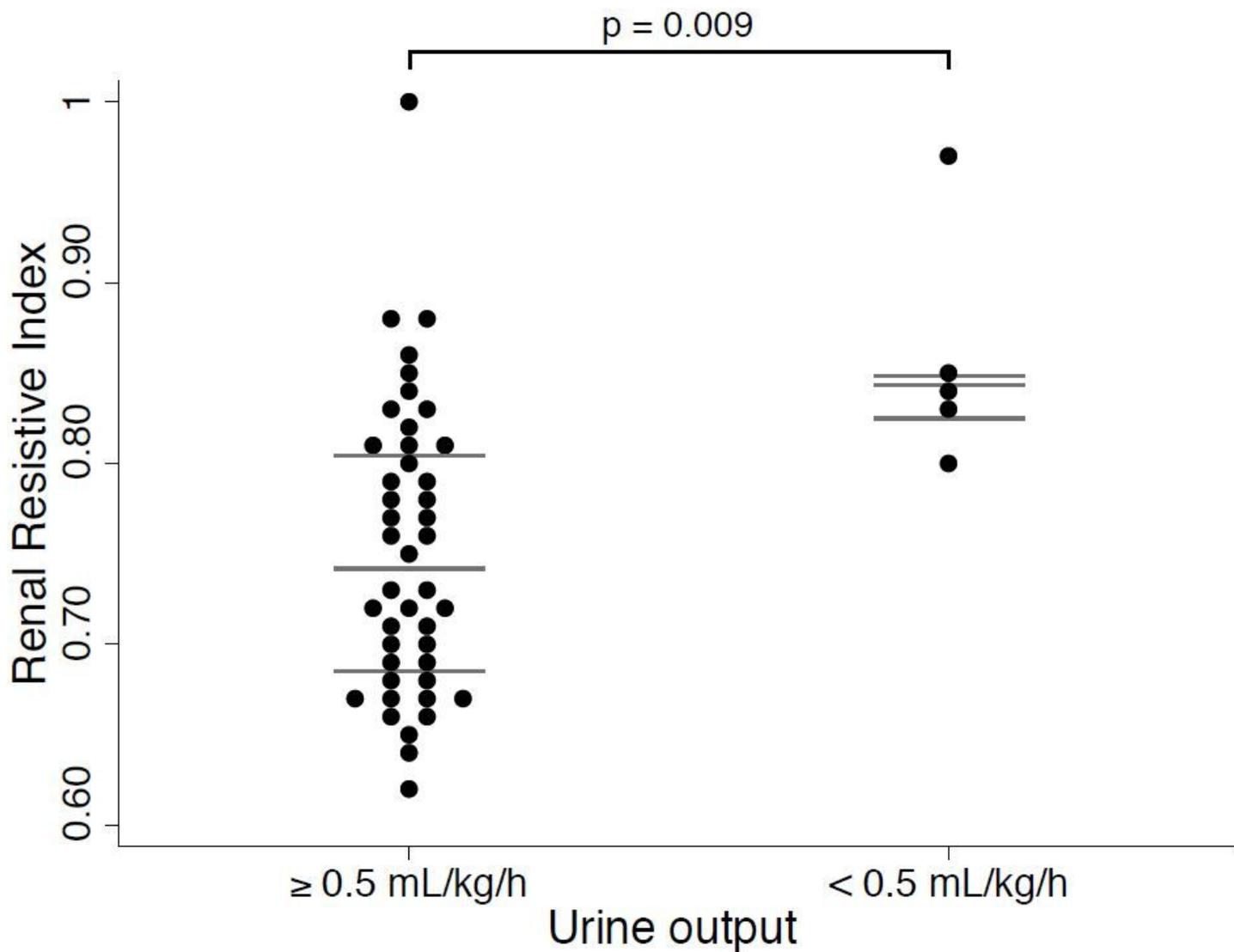
**Figure 2**

Dot plot illustrating the association between renal resistive index and acute kidney injury (AKI) in patients with or without AKI (left) and patients with different stages of AKI (right). Each dot represents a patient. The horizontal lines represent the median, upper and lower quartiles.



**Figure 3**

Dot plot illustrating the association between renal resistive index and acute kidney injury (AKI) in patients who did not develop AKI, developed AKI but recovered, and had an ongoing AKI episode at the time of measurement. Each dot represents a patient. The horizontal lines represent the median, upper and lower quartiles.



**Figure 4**

Dot plot illustrating the association between renal resistive index and oliguria defined as urine output  $< 0.5$  ml/kg ideal body weight/hour for 24 hours. Each dot represents a patient. The horizontal lines represent the median, upper and lower quartiles.