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Research Paper

The spectrum of biochemical alterations associated with organ dysfunction and inflammatory status and their association with disease outcomes in severe COVID-19: A longitudinal cohort and time-series design study

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ABSTRACT

Background: In patients with severe COVID-19, no data are available on the longitudinal evolution of biochemical abnormalities and their ability to predict disease outcomes.
Methods: Using a retrospective, longitudinal cohort study design on consecutive patients with severe COVID-19, we used an extensive biochemical dataset of serial data and time-series design to estimate the occurrence of organ dysfunction and the severity of the inflammatory reaction and their association with acute respiratory failure (ARF) and death.
Findings: On the 162 studied patients, 1151 biochemical explorations were carried out for up to 59 biochemical markers, totaling 15,260 biochemical values. The spectrum of biochemical abnormalities and their kinetics were consistent with a multi-organ involvement, including lung, kidney, heart, liver, muscle, and pancreas, along with a severe inflammatory syndrome. The proportion of patients who developed an acute kidney injury (AKI) stage 3, increased significantly during follow-up (0·9%, day 0; 21·4%, day 14; $P<0·001$). On the 20 more representative biochemical markers (>250 iterations), only CRP >90 mg/L (odds ratio [OR] 6·87, 95% CI, 2·36–20·01) and urea nitrogen >0·36 g/L (OR 3·91, 95% CI, 1·15–13·29) were independently associated with the risk of ARF. Urea nitrogen >0·42 g/L was the only marker associated with the risk of COVID-19 related death.
Interpretation: Our results point out the lack of the association between the inflammatory markers and the risk of death but rather highlight a significant association between renal dysfunction and the risk of COVID-19 related acute respiratory failure and death.
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Research in context

Evidence before this study

We performed a literature search to assess the available data regarding the follow-up of multi-organ dysfunction and inflammatory status using biochemical biomarkers kinetics in patients with severe COVID-19. We searched PubMed from inception to April 4, 2020, for studies that have reported clinical and biological data, and disease outcomes in patients with COVID-19. In patients with severe COVID-19, no data are available on the follow-up of multi-organ dysfunction and inflammatory status by assessing the kinetics of biochemical biomarkers and its association with disease-related complications.

Added value of this study

In this retrospective cohort study on 162 consecutive patients with newly diagnosed severe COVID-19, we report the first longitudinal analysis using an extensive biochemical dataset of serial data (59 biochemical markers; 15,260 biochemical measures) and time-series design to estimate the occurrence of organ dysfunction and the severity of the inflammatory reaction and their association with acute respiratory failure (ARF) and death. Among all the studied biomarkers, only urea nitrogen and C-reactive protein (CRP) were independently associated with acute respiratory failure.

Implications of all the available evidence

In patients with newly diagnosed severe COVID-19, the follow-up of biochemical biomarkers kinetics was consistent with a severe multi-organ involvement along with a severe acute inflammatory response. Our study pointed out new biochemical abnormalities targeting other organs than lungs and kidneys, including the liver and biliary tract with marked cholestatic syndromes. High levels of CRP and urea nitrogen were potential predictors of acute respiratory failure among patients with severe COVID-19.

1. Introduction

A novel human coronavirus, called severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), causing the disease COVID-19 (according to the WHO nomenclature, for coronavirus disease 2019) was identified in China in December 2019 [1]. The pandemic has rapidly progressed from China to all continents with more than 180 countries concerned in mid-April 2020, with 1777,666 identified cases and 108,867 COVID-19 related deaths [2]. During January 2020, three cases of COVID-19 were confirmed in France as the first cases in Europe [3]. During March 2020, the COVID-19 epidemic has rapidly spread in France, notably from an epidemic cluster in the North East of France with 130,730 identified cases and 13,851 deaths by mid-April 2020 [2]. Several papers reported the baseline characteristics, the clinical findings, and outcomes of patients with COVID-19 from China [4-9], Singapore [10], and Italy [11]. These studies assessed the clinical and demographic factors of patients with the COVID-19 and pointed out an increased risk of mortality among older males and patients with co-morbidities [4-11]. Pulmonary, systemic inflammation and subsequent multi-organ dysfunction have been reported in association with severe COVID-19 [8]. Acute respiratory distress syndrome with respiratory failure requiring mechanical ventilation and acute cardiac injury with heart failure were the most common critical complications potentially leading to death in patients with severe COVID-19 [8].

In patients with severe COVID-19, no data are available on the longitudinal follow-up of organ dysfunction and inflammation by assessing the kinetics of biochemical biomarkers using a time-series design. Furthermore, even if some studies have evaluated the risk of COVID-19 related complications using a small set of biological markers at baseline, no study has evaluated, on a wide range of biochemical markers, the spectrum and the magnitude of biochemical disturbances, as well as their kinetics over time and their potential association with disease outcomes in patients with severe COVID-19. Using a big-data approach and multilevel modeling adapted for repeated measures on a well-phenotyped retrospective cohort of consecutive patients with newly diagnosed severe COVID-19, we were able to assess the occurrence of organ dysfunction (kidney, lung, heart, liver, muscle) and the severity of the inflammatory reaction as evaluated by biomarker kinetics in hospitalized patients. We assessed the association of the more representative biochemical markers with the risk of occurrence of ARF and death.

2. Methods

2.1. Study design, setting, and patients' inclusion criteria

We carried out a retrospective, longitudinal cohort study, and time-series design on all newly diagnosed consecutive patients among the first cases of severe COVID-19 that required hospitalization at the University Hospital of Nancy. Inclusion in the cohort began on the day of hospital admission, and each patient was then followed until discharge from hospital or death if it occurred during hospitalization. The inclusion criteria were: i) diagnosis of COVID-19 based on the detection of SARS-CoV-2 ribonucleic acids (RNA) from nasopharyngeal swabs; ii) severe COVID-19 defined by an oxygen saturation of 94% or less while the patient was breathing ambient air or a need for oxygen support [12,13]; iii) hospitalization in one of the healthcare departments of the University Hospital of Nancy from March 1, 2020, to March 25, 2020. The final date of follow-up was March 31, 2020. The cohort was observational, i.e., all clinical assessments, biochemical explorations, imaging examinations, and clinical diagnoses were carried out at the discretion of the treating physicians as part of the standards of care of patients with suspected COVID-19 during the study period at the University Hospital of Nancy (see Supplementary Methods). The Ethics committee of the University Hospital of Nancy approved the study.

2.2. Description of the Nancy biochemical database

As previously reported [14], the "Nancy Biochemical Database" is a prospectively maintained electronic database that increments the biochemical results of consecutive patients hospitalized in 67 healthcare departments at the University Hospital of Nancy (**Supplementary Fig. 1**). The biochemical data are connected to clinical data at the patient level through the electronic health record system of the University Hospital of Nancy. All biochemical data that were obtained in patients with COVID-19 were extracted for the purposes of the study using the GLIMS laboratory information management system v9 (MIPS France S.a.r.l., Paris, France). Clinical data were retrieved through electronic chart review using DxCare® software (Dedalus France, Le Plessis Robinson, France). All biochemical investigations were prescribed at the discretion of the treating physicians from each healthcare department. The "Nancy Biochemical Database" is registered at the French National Commission on Informatics and Liberty, CNIL, under the record N°1763197v0. The Ethics committee of the University Hospital of Nancy approved the study (ID: 2020/264).

2.3. Data collected for the study

The following data were available in the Nancy Biochemical Database: patient identification number, patient's age at hospital

admission, date and time of blood sampling, patient health care department. A total of 59 biochemical markers were available, with 46 in the blood and 13 in the urine. The biochemical markers available in blood were: *electrolytes, renal markers*: sodium (mmol/L), potassium (mmol/L), chloride (mmol/L), creatinine (mg/L), urea nitrogen (g/L), phosphorus (mg/L), calcium (mg/L), magnesium (mg/L), calculated and measured (mOsmol/kg), uric acid (mg/L), phosphorus reabsorption rate (%), fractional excretion of sodium (%), fractional excretion of potassium (%), fractional excretion of chloride (%), and anionic gap (mmol/L); *blood gas*: hemoglobin (g/dL), partial pressure of oxygen (PO_2) (mmHg), partial pressure of carbon dioxide (PCO_2) (mmHg), pH, bicarbonate (HCO_3^-) (mmol/L), and lactate (mmol/L); *liver, pancreas*: aspartate aminotransferases (ASAT) (U/L), alanine aminotransferases (ALAT) (U/L), total bilirubin (mg/L), conjugated bilirubin (mg/L), alkaline phosphatase (UI/L), γ-glutamyltransferase (U/L), and lipase (U/L); *inflammatory markers*: C-reactive protein (CRP) (mg/L), procalcitonin (ng/ml), and interleukin 6 (pg/mL); *iron markers*: ferritin (μg/L), iron-binding capacity saturation (%), iron (mg/L), and transferrin (g/L); *cardiac markers*: high-sensitivity cardiac troponin I (hs-c Troponin I) (pg/mL), N-Terminal pro-Brain Natriuretic Peptide (NT-proBNP) (pg/mL); *muscle markers*: lactate dehydrogenase (U/L), creatine kinase (U/L); *nutritional markers*: total protein (g/L), albumin (g/L), prealbumin (g/L), glucose (g/L), triglycerides (g/L), and cholesterol (g/L). The biochemical markers available in the urine were: sodium (mmol/L), potassium (mmol/L), chloride, urine (mmol/L), creatinine (mg/L), urea nitrogen (g/L), glucose (g/L), proteins (g/L), anion gap (mmol/L), uric acid (mg/L), osmolality (mOsmol/kg), phosphorus (mg/L), calcium (mg/L), and microalbumin (mg/L). The following clinical data were available: date of hospital admission; patient's medical history (hypertension, type 2 diabetes, cardiovascular disease, vascular disease, dyslipidemia, chronic obstructive pulmonary disease, obstructive sleep apnea syndrome, asthma, cancer, and chronic kidney disease); patient's outcome during the hospitalization for the management of COVID-19 (acute respiratory failure [ARF] as defined by the treating physicians [15-17], intubation with mechanical ventilation, pulmonary embolism, and in-hospital mortality related to the COVID-19, defined as the occurrence of death in relation with a complication of the COVID-19 [18]).

2.4. Molecular detection of SARS-CoV-2

After viral RNA extraction from nasopharyngeal swabs, the procedure applied for the detection of SARS-CoV-2 genome was based on primers and probes designed to target the RdRp gene spanning nucleotides 12,621−12,727 and 14,010−14,116 (positions according to SARS-CoV, NC_004718, National reference Center for Respiratory Viruses, Pasteur Institute, Paris, France; sequences available on request). Each real-time reverse transcriptase-polymerase chain reaction (RT-qPCR) included negative and positive samples (in vitro synthesized RNA transcripts). The RT-PCR assay sensitivity was around 100 copies of RNA genome equivalent. Regarding the specificity of the test, none of the tested respiratory viruses showed reactivity to influenza A-B, respiratory syncytial virus, bocavirus (hBoV), metapneumovirus (hMPV), HRV/enterovirus, adenovirus, and other coronaviruses (HCoV: KU1, OC43, 229E, and NL63). All the virological diagnoses of SARS-CoV-2 infection were carried out at the Division of Virology of the University Hospital of Nancy, which served as one of the two regional reference centers for the SARS-CoV-2 diagnosis in North East of France.

2.5. Biochemistry assays

Biochemistry analyses were performed on Atellica immunoassay (IM) and clinical chemistry (CH) multiparametric analyzers (Siemens Healthcare SAS, France). Blood gas analyses were performed on ABL800 FLEX analyzers (Radiometer France SAS, France).

2.6. Standards of care of patients with suspected COVID-19 during the study period at the university hospital of Nancy

At the University Hospital of Nancy, during March 2020, the recommended best standard of care for suspected COVID-19 patients requiring hospital admission for non-critical respiratory failure included a systematic diagnostic workup with a clinical and biological assessment, molecular detection of SARS-CoV-2 by real-time reverse transcriptase-polymerase chain reaction (RT-qPCR), blood and sputum cultures, and chest CT-scan. Patients were managed according to National Health Authority guidelines, including the following items: i) oxygen delivery to maintain peripheral capillary oxygen saturation (SpO_2) >90%, ii) 48 h of probabilistic antibiotic therapy combining cefotaxime with spiramycin awaiting SARS-CoV-2 RT-qPCR result and bacteriological assessment; iii) therapeutic dose of antithrombotic therapy using low molecular weight heparin or unfractionated heparin in case of renal failure. All other aspects related to the standards of care and patients' monitoring are detailed in Supplementary Methods).

2.7. Study aims and endpoints

The primary aim was to assess the occurrence of organ dysfunction (kidney, lung, heart, liver, and muscle) and the severity of the inflammatory reaction as evaluated by biomarker kinetics in patients with severe COVID-19. The secondary aims were to assess the biochemical markers potentially associated with: i) COVID-19 related ARF, and ii) in-hospital mortality related to the COVID-19. For each studied biochemical marker, the primary endpoint was the percentage of time above or below the upper or the lower reference limit, respectively, during the hospital stay. The most frequently observed biochemical abnormalities were defined as those that were observed more than 25% of time above or below the upper or the lower reference limit, respectively. For the prognostic objective (secondary aim), the endpoints were: i) the occurrence of COVID-19 related ARF as defined by the treating physicians [15-17] and ii) in-hospital mortality related to the COVID-19, defined as the occurrence of death in relation with a complication of the COVID-19 [18]. The diagnosis and severity of acute kidney injury (AKI) were classified according to the AKI network criteria, based on the results of serum creatinine [19].

2.8. Statistical analyses

All quantitative variables are shown as the median and interquartile range (IQR, 25−75th percentile) and qualitative variables as percentages and 95% confidence interval (95% CI). The kinetics over time of the studied biochemical markers was modeled using the isotonic regression method, which was estimated using the pool adjacent violators algorithm [20,21]. The pool adjacent violators algorithm is a linear time algorithm for linear ordering isotonic regression [21]. Using a multistep approach, we evaluated a set of 20 biochemical markers with a sufficiently high number of iterations (n >250, study power analysis reported in Supplementary Methods) to assess the relationship between their variation over time and the occurrence of the endpoint (ARF, death). In *step #1*, for each biochemical variable, we assessed the optimal threshold using receiver operating characteristic (ROC) analysis, according to DeLong et al. [22]. The classification variable used in the ROC analysis was the studied endpoint. The optimal diagnostic cut-off was defined using the Youden index J. Bias-corrected and accelerated (BC_a)-bootstrap interval after 10,000 iterations for the Youden index and its associated values were performed [23]. We used Bonferroni's correction to account for multiple comparisons. In *step #2*, all the variables that were significantly associated with the studied endpoint in ROC analyses were assessed using time-series analysis [24]. The evolution times were calculated from the first day of biochemical assessment and were expressed in days.

The time-series analysis aimed to compare the percentage of time below or above the ROC-defined threshold between two patients' subgroups according to the presence or absence of the studied endpoint. The calculated summary effects were reported as percentages of the total time of observation with the 95% confidence interval (95% CI). Normality testing was performed using the D'Agostino-Pearson test. Subgroups comparison regarding the percentage of time below or above the prespecified threshold was carried out using the Student's *t*-test or the Mann-Whitney *U* test according to the parametric or nonparametric distribution of the variables, respectively. In *step #3*, we looked for independent predictors using multivariable multilevel analysis. All the predictors that were still significant at the step #2 were assessed using a two-level hierarchical logistic model (HLM), which enabled to take into account the correlation between all the studied biochemical markers, which correspond to the level 1 of the HLM, and the patient-level characteristics, which correspond to the level 2 of the HLM (i.e., age, gender, patient's medical history) [25]. For each endpoint of interest, a multivariable model was then constructed following the modeling strategy recommended for HLM [26]. We estimated the empty model without level 1 or level 2 variables to confirm the relevance of using the HLM assumption, which is based on a median odds ratio $>>1$, considering a variable number of iterations between each patient [27]. Each biochemical variable (level 1, HLM) was tested for the association with the endpoint using bivariate analyses at a 0·2 threshold. A stepwise backward multivariable selection procedure was used to retain the variables associated with the endpoint at a 0·05 threshold, without adjustment for patient-level characteristics (level 2, HLM). Random slopes on the significant biochemical variables retained in the HLM model were tested for their association with the endpoint, considering the between-patient variability. While alternative procedures exist to build models, the procedure we applied has been shown to be the most suitable one for HLM specification (data not shown) [28]. At the final step of the HLM, eligible patient characteristics (level 2) on collinearity testing were incremented in the validated HLM model, and cross-level interactions, i.e., interactions between time measurement and patients variables, were tested in the full model (level 1 and level 2). The HLM model was estimated using the predictive quasi-likelihood method. For each variable retained in the full HLM model, summary measures were reported as odds ratio (OR), 95% CI, and the associated *P*-value. Statistical analyses other than the multivariate model analysis were performed using MedCalc for Windows, version 19.1 (MedCalc Software, Ostend, Belgium) based on a two-sided type I error with an alpha level of 0·05. The multivariate model analysis was performed using SAS 9.4 (SAS Institute, Cary, NC, USA).

2.9. Role of funding source

This research received no specific grant from any funding agency.

3. Results

3.1. Study population, database structure, and main biochemical abnormalities observed in severe COVID-19

Between March 1, 2020, and March 25, 2020, 162 patients were admitted to one of the healthcare departments of the University Hospital of Nancy for severe COVID-19 (**Supplementary Table 1**). The median age was 66 (IQR, 56 to 77) years, and the proportion of males was 59% (**Table 1**). No patient received hydroxychloroquine or remdesivir. During the study period, 1151 biochemical explorations were carried out for up to 59 biochemical markers (46 in the blood and 13 in the urine), totaling 15,260 biochemical values. The distribution of the 59 biochemical markers is reported in **Table 2** (blood) and **Supplementary Table 2** (urine). The kinetics over time of the biochemical abnormalities is reported in Figs. 1, 2 and 3 **and Supplementary Figs. 2–4** for blood parameters and in **Supplementary Fig. 5** for urine parameters. The most frequently observed biochemical abnormalities during the follow-up were (≥25% of the observed time): increased urea nitrogen, hyperosmolality, hypocalcemia, low hemoglobin, hypoxemia; major cytolysis with severe cholestatic syndromes and conjugated hyperbilirubinemia; increased C-reactive protein (CRP); increased cardiac (high-sensitivity cardiac troponin I, NT-proBNP: N-Terminal pro-Brain Natriuretic Peptide) and muscle (lactate dehydrogenase, creatine kinase) markers; and hypoalbuminemia with hypertriglyceridemia (**Table 2 and** Figs. 1, 2 and 3). The evolution of phosphorus followed a biphasic curve with a decrease during the first four days, followed by a progressive increase in parallel with urea nitrogen and creatinine. The proportion of patients who developed an acute kidney injury (AKI) stage 3, according to the AKI classification, increased significantly over time (0·9%, day 0; 13·6%, day 7; and 21·4%, day 14; $P < 0{\cdot}001$) (**Supplementary Fig. 6** and **Supplementary Table 3**). Other biochemical abnormalities (10–24% of the observed time) included hypernatremia, hyperkalemia, hyperchloremia, increased creatinine, hypoproteinemia, hyperlactatemia, hyperlipasemia, and increased procalcitonin (**Table 2 and Supplementary Figs. 2–4**).

Table 1
Characteristics of the patients with severe COVID-19.

Demographics		
Age (years) — N, median (IQR)	162	66 (56–77)
Male gender — n/N,% (95% CI)	96/162	59% (52–67)
Patients' medical history — n/N,% (95% CI)		
Hypertension	68/135	50% (42–59)
Type 2 diabetes	39/135	29% (21–37)
Cardiovascular disease	38/135	28% (21–36)
Vascular disease	37/135	27% (20–35)
Dyslipidemia	32/135	24% (16–31)
Chronic obstructive pulmonary disease	17/135	13% (7–18)
Obstructive sleep apnea syndrome	17/135	13% (7–18)
Asthma	8/135	6% (2–10)
Cancer	8/135	6% (2–10)
Chronic kidney disease	8/135	6% (2–10)
Outcomes — n/N,% (95% CI)		
Acute respiratory failure	76/149	51% (43–59)
Intubation and mechanical ventilation	54/149	36% (28–44)
COVID-19 related death	21/149	14% (8–20)
Pulmonary embolism	2/149	1% (0–3)

Note. IQR: interquartile range 25th – 75th; N: number of patients; n: number of observations;%: percentage; 95% CI: 95% confidence interval.

3.2. Factors associated with an occurrence of acute respiratory failure related to severe COVID-19

On the 20 biochemical variables assessed in ROC analysis, 15 were significantly associated with the risk of ARF after Bonferroni correction (**Table 3 and Supplementary Fig. 7**). All the 15 dichotomized variables differed significantly in time-series analyses between patients with or without ARF, with a significantly higher proportion of time with the biochemical marker above or under the ROC-defined threshold among patients with ARF when compared to patients without ARF (**Table 3** and **Fig. 4**). These markers included electrolyte and blood gas disturbances, increased renal markers, liver and muscle cytolysis, severe inflammatory syndrome, and hypoproteinemia. In the multivariable multilevel analysis, three variables were independently associated with the risk of ARF, namely: CRP >90 mg/L (OR, 6·87 [95% CI, 2·36–20·01]; $P < 0{\cdot}001$), urea nitrogen >0·36 g/L (OR, 3·91 [95% CI, 1·15–13·29]; $P = 0{\cdot}03$), and the medical history of type

Table 2
Distribution of the 46 biochemical markers in the blood in patients with severe COVID-19.

Electrolytes, renal markers	*N*	Median	IQR, 25th – 75th	Reference Values[a]	% of time, < lower limit	% of time, > upper limit
Sodium (mmol/L)	848	141	138–144	136–145	8·7 (5·2–12·1)	12·9 (9·2–16·7)
Potassium (mmol/L)	854	4·00	3·68–4·38	3·40–4·50	8·6 (5·7–11·5)	11·0 (7·9–14·2)
Chloride (mmol/L)	799	104	101–107	98–107	5·7 (3·0–8·4)	21·5 (16·3–26·8)
Creatinine (mg/L)	845	8·0	6·0–11·9	M: 7–13 F: 5·5–10·2	M: 20·6 (13·7–27·5) F: 22·7 (13·8–31·5)	M: 19·0 (12·2–26·0) F: 10·7 (3·7–17·7)
Urea nitrogen (g/L)	844	0·43	0·26–0·75	0·19–0·49	7·7 (4·3–11·3)	28·7 (22·5–34·9)
Phosphorus (mg/L)	299	30·96	25·08–38·39	24–51	12·6 (7·4–17·7)	5·6 (1·8–9·5)
Calcium (mg/L)	266	83·6	79·6–88·0	87–104	38·7 (29·7–47·7)	1·3 (0–3·3)
Magnesium (mg/L)	164	20·4	18·0–23·7	16–26	4·8 (0·5–9·1)	8·4 (3·0–13·7)
Osmolality, calculated (mOsmol/kg)	240	297	289–307	282–290	2·6 (0–7·8)	26·9 (18·9–35·0)
Osmolality, measured (mOsmol/kg)	40	295·5	289–317	282–290	Low sample size	Low sample size
Uric acid (mg/L)	82	44	30–62	M: 37–92 F: 31–78	Low sample size	Low sample size
Phosphorus reabsorption rate (%)	27	82·4	71–88	>85%	Low sample size	Not applicable
FENa (%)	28	0·3	0·15–0·75	1–2	Low sample size	Low sample size
FEK (%)	29	7·2	5·38–13·10	4–16	Low sample size	Low sample size
FECl (%)	23	0·7	0·22–1·45	–	Low sample size	Low sample size
Anionic gap (mmol/L)	33	14·5	13·3–15·7	10 – 16	Low sample size	Low sample size

Blood gas	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
Hemoglobin (g/dL)	787	11·8	10·4–13·6	M: 13·5–17·5 F: 12·0–16·0	M: 50·0 (40·8–59·1) F: 35·3 (22·6–48·0)	M: 4·1 (1·6–6·6) F: 3·9 (0·3–7·4)
PO_2 (mmHg)	784	77·7	66·8–94·6	80–100	41·3 (35·0–47·7)	14·0 (10·5–17·4)
PCO_2 (mmHg)	785	38·8	33·9–45·5	35–45	25·3 (19·1–31·5)	14·7 (10·3–19·1)
pH	785	7·43	7·39–7·47	7·37–7·43	10·5 (6·9–14·2)	43·9 (36·9–50·9)
Bicarbonate (mmol/L)	762	25·7	23·1–28·5	M: 22·2–28·3 F: 21·2–27·0	M: 14·6 (8·4–20·8) F: 7·3 (0·7–13·9)	M: 18·4 (12·3–24·5) F: 12·4 (4·0–20·8)
Lactate (mmol/L)	715	1·2	0·9–1·5	0·5–1·6	0·7 (0–1·5)	15·6 (11·0–20·2)

Liver, pancreas	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
ASAT (U/L)	492	60·5	36–95	13–40	0·8 (0–2·0)	47·0 (39·3–54·6)
ALAT (U/L)	491	54	31–98	7–40	0 (–)	43·1 (35·4–50·8)
Bilirubin, total (mg/L)	466	6·4	4·7–9·9	2·0–11·0	1·3 (0–3·1)	12·4 (7·5–17·3)
Bilirubin, conjugated (mg/L)	108	11	6·0–18·0	1·0–3·0	0 (–)	60·9 (53·1–68·7)
Alkaline phosphatase (UI/L)	196	69·5	51–102	46–116	7·1 (2·6–11·6)	9·1 (3·9–14·5)
γ-glutamyltransferase (U/L)	161	60	27–164	M: ≤73 F: ≤38	M: Not applicable F: Not applicable	M: 31·4 (18·0–44·7) F: 20·4 (7·4–33·3)
Lipase (U/L)	49	47	36–76	12–53	0 (–)	14·2 (3·0–25·4)

Inflammatory markers	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
C-reactive protein (mg/L)	388	80·5	30·5–147·2	≤10	Not applicable	60·4 (52·6–68·2)
Procalcitonin (ng/ml)	94	0·2	0·09–0·91	≤0·05	Not applicable	20·7 (11·1–30·3)
Interleukin 6 (pg/mL)	16	95·47	59·8–223·9	≤6·4	Not applicable	Low sample size

Iron markers	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
Ferritin (μg/L)	107	1358	685–2281	M: 22–322 F: 10–291	Low sample size	Low sample size
Iron-binding capacity, saturation	12	12·0	6·0–16·5	20–40	Low sample size	Low sample size
Iron (mg/L)	12	0·23	0·14–0·34	M: 0·65–1·75 F: 0·5–1·7	Low sample size	Low sample size
Transferrin (g/L)	12	1·40	1·20–1·75	M: 2·15–3·65 F: 2·5–3·8	Low sample size	Low sample size

Cardiac markers	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
hs-c Troponin I (pg/mL)	255	21·0	7·5–80·7	M: ≤24 F: ≤12	Not applicable	M: 36·5 (25·9–47·2) F: 20·8 (7·2–34·4)
NT-proBNP (pg/mL)	232	589	143–2459	<75 y: <125 >75 y: <450	Not applicable	<75 y: 39·5 (28·0–51·1) >75 y: 50·5 (34·0–67·0)

Muscle markers	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
LDH (U/L)	155	373	285–444	120–246	0 (–)	33·0 (23·4–42·6)
Creatine kinase (U/L)	272	148	69–434	M: 46–171 F: 34–145	M: 6·3 (1·7–10·9) F: 12·9 (0·6–25·2)	M: 36·7 (26·2–47·2) F: 14·3 (2·8–25·8)

(*continued*)

Table 2 (*Continued*)

Muscle markers	*N*	Median	IQR, 25th – 75th	Reference values[a]	% of time, < lower limit	% of time, > upper limit
Proteins, total (g/L)	744	60	55–65	57–82	21·4 (16·0–26·7)	0 (–)
Albumin (g/L)	134	27·2	23·2–31·0	35–52	30·3 (21·2–39·5)	0 (–)
Prealbumin (g/L)	51	0·06	0·05–0·14	0·1–0·4	Low sample size	Low sample size
Glucose (g/L)	625	1·23	1·03–1·60	0·74–1·06	Not relevant	Not relevant
Triglycerides (g/L)	133	1·87	1·4–2·4	<1·5	Not applicable	42·8 (29·5–56·2)
Cholesterol (g/L)	16	1·26	1·00–1·60	Desirable, <2	Not applicable	Low sample size

Note. IQR: interquartile range; M: males; F: females; ASAT: aspartate aminotransferases; ALAT: alanine aminotransferases; FENa: fractional excretion of sodium; FEK: fractional excretion of potassium; FECl: fractional excretion of chloride; hs-c Troponin I: high-sensitivity cardiac troponin I; LDH: lactate dehydrogenase; NT-proBNP: N-Terminal pro-Brain Natriuretic Peptide; PO_2: partial pressure of oxygen; PCO_2: partial pressure of carbon dioxide.
[a] The reference values are adapted to an adult population.

Table 3
Biochemical markers associated with the occurrence of acute respiratory failure among patients with severe COVID-19 disease in bivariate analyses.

Biological variable	n	ROC, *P*-value[a]	AUROC[a]	ROC-defined cut-off	Time-series analysis *P*-value[b]	Percentage of time according to the threshold (95% CI), No ARF	Percentage of time according to the threshold, (95% CI), ARF
Sodium (mmol/L)	854	0·68	0·509 (0·466–0·554)	–	–	–	–
Potassium (mmol/L)	854	<0·001[c]	0·588 (0·544–0·632)	>3·7	<0·001	43·1 (32·9–53·4)	70·1 (62·6–77·6)
Chloride (mmol/L)	799	<0·001[c]	0·589 (0·539–0·635)	≤104	<0·001	27·0 (17·2–36·9)	45·2 (36·3–54·2)
Urea nitrogen (g/L)	844	<0·001[c]	0·729 (0·687–0·767)	>0·36	<0·001	25·1 (15·3–34·8)	62·3 (52·8–71·9)
Creatinine (mg/L)	845	<0·001[c]	0·610 (0·566–0·650)	>9·7	0·002	18·8 (9·9–27·6)	34·7 (25·2–44·3)
Hemoglobin (g/dL)	787	<0·001[c]	0·706 (0·644–0·758)	≤12·7	<0·001	18·5 (7·9–29·1)	56·6 (47·6–65·6)
pH	785	<0·001[c]	0·643 (0·584–0·701)	≤7·41	<0·001	7·9 (0·1–15·7)	32·1 (24·6–39·5)
pO_2 (mm/Hg)	785	<0·001[c]	0·643 (0·581–0·699)	>80·8	<0·001	14·5 (5·4–23·6)	43·7 (36·6–50·7)
pCO_2 (mmHg)	785	<0·001[c]	0·701 (0·642–0·753)	>38·8	<0·001	9·0 (0·8–17·3)	43·9 (34·7–53·2)
Bicarbonate (HCO_3^-) (mmol/L)	762	<0·001[c]	0·640 (0·590–0·688)	>26·6	<0·001	7·2 (0–14·4)	34·4 (25·7–43)
Lactates (mmol/L)	715	0·58	0·521 (0·446–0·594)	–	–	–	–
ASAT (U/L)	492	<0·001[c]	0·740 (0·682–0·791)	>48	<0·001	18·1 (8·6–27·5)	59·2 (49·2–69·1)
ALAT (U/L)	491	<0·001[c]	0·676 (0·614–0·734)	>38	<0·001	21·8 (11·2–32·5)	63·2 (53–73·4)
Bilirubin, total (mg/L)	466	0·70	0·512 (0·453–0·571)	–	–	–	–
Total proteins (g/L)	744	<0·001[c]	0·687 (0·639–0·733)	≤61	<0·001	15·9 (8·1–23·8)	57·8 (48·8–66·7)
C-reactive protein (mg/L)	388	<0·001[c]	0·761 (0·709–0·807)	>90	<0·001	10·8 (4·2–17·5)	49·5 (37·9–61·1)
Calcium (mg/L)	266	<0·001[c]	0·825 (0·755–0·876)	≤83·6	<0·001	4·3 (0–10·9)	46·2 (35·1–57·4)
Phosphorus (mg/L)	299	0·20	0·553 (0·471–0·635)	–	–	–	–
hs-c Troponin I (pg/mL)	255	0·14	0·572 (0·474–0·665)	–	–	–	–
CK (U/L)	272	<0·001[c]	0·670 (0·591–0·741)	>331	<0·001	2·6 (0–6·8)	28·8 (18·9–38·6)

Note. ARF: acute respiratory failure; AUROC: area under the receiver operating characteristic curve; ASAT: aspartate aminotransferases; ALAT: alanine aminotransferases; CK: creatine kinase; hs-c Troponin I: high-sensitivity cardiac troponin I; PO_2: partial pressure of oxygen; PCO_2: partial pressure of carbon dioxide; ROC: receiver operating characteristics.
[a] Receiver operating characteristic (ROC) analysis, according to DeLong et al. with Bias-corrected and accelerated (BCa)-bootstrap interval after 10,000 iterations for the Youden index.
[b] Time-series analysis using a non-parametric test.
[c] All nominal *P*-values maintained their significance after Bonferroni correction.

2 diabetes (OR, 4·49 [95% CI, 1·07–18·89]; $P = 0·04$) (Table 4). In the alternative model, that used creatinine instead of urea nitrogen to avoid collinearity, CRP >90 mg/L, and the medical history of type 2 diabetes were independently associated with the risk of ARF (Table 4).

3.3. Factors associated with in-hospital mortality related to severe COVID-19

On the 20 biochemical variables assessed in ROC analysis, five were significantly associated with the risk of death after Bonferroni correction (Table 5). In time-series analyses, among the five dichotomized variables, only one differed significantly between patients who died or not: urea nitrogen >0·42 g/L (Table 5 and Fig. 5). In the multivariable multilevel analysis, only age (OR, 1·12 [95% CI, 1·03–1·22]; $P = 0·006$) and medical history of chronic obstructive pulmonary disease (OR, 14·06 [95% CI, 1·08–182·74]; $P = 0·04$) were significantly associated with the risk of COVID-19 related death. Urea nitrogen >0·42 g/L had an OR of 3·64 (95% CI, 0·71–18·71; $P = 0·12$) for the association with in-hospital mortality (Table 4).

4. Discussion

Using a big-data approach and time-series design on a well-phenotyped retrospective cohort of consecutive patients with newly diagnosed SARS-CoV-2 infection, we were able to describe the most frequently observed biochemical abnormalities over time in patients with severe COVID-19. In these patients, the kinetics of biochemical abnormalities was consistent with a multi-organ involvement (Fig. 6). The results of our study point out the lack of the association between the inflammatory markers and the risk of death but rather highlight a significant association between renal dysfunction and the risk of COVID-19 related ARF or death.

A cohort study from China reported a baseline prevalence of acute kidney injury among 5·1% of patients with COVID-19 that were admitted to a tertiary hospital [29]. Patients with an AKI stage 1 to 3 were at a higher risk of in-hospital mortality [29]. One of the

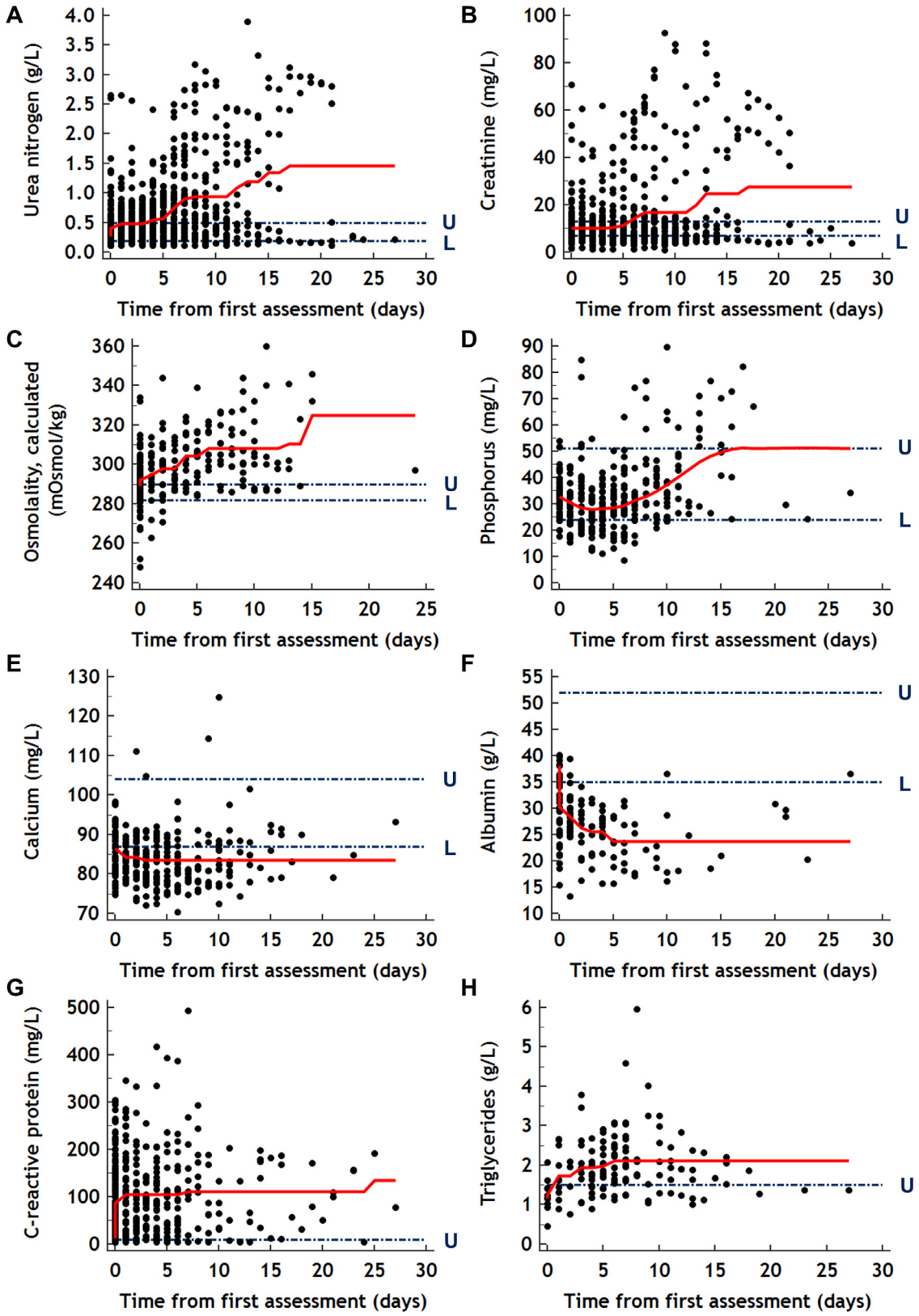

Fig. 1. *Kinetics over time of the most frequently observed biochemical abnormalities during the follow-up of patients with severe COVID-19 (part 1)*: **A**: urea nitrogen (g/L); **B**: creatinine (mg/L); **C**: osmolality, calculated (mOsmol/kg); **D**: phosphorus (mg/L); **E**: calcium (mg/L); **F**: albumin (g/L); **G**: triglycerides (g/L); and **H**: C-reactive protein (mg/L). The dashed lines correspond to the upper (U) and lower (L) limits of the reference range. The red line indicates the evolution trend of the biomarker during follow-up according to the isotonic regression method.

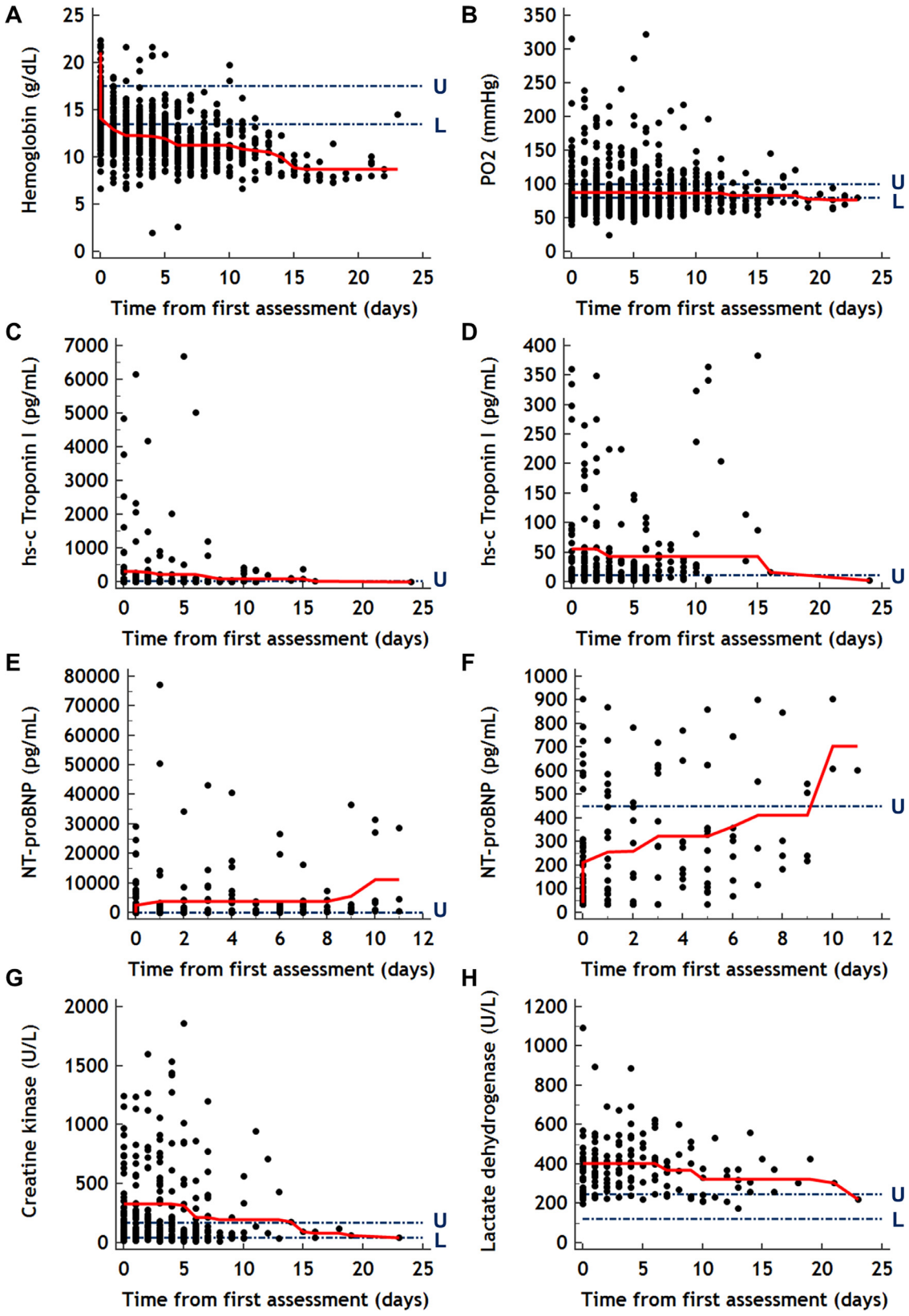

Fig. 2. *Kinetics over time of the most frequently observed biochemical abnormalities during the follow-up of patients with severe COVID-19 (part 2)*: **A**: hemoglobin (g/dL); **B**: partial pressure of oxygen (PO_2) (mmHg); **C**: high-sensitivity cardiac troponin I (hs-c Troponin I) (pg/mL); **D**: hs-c Troponin I (view limited to hs-c Troponin *I* <400 pg/mL); **E**: N-Terminal pro-Brain Natriuretic Peptide (NT-proBNP) (pg/mL); **F**: NT-proBNP (view limited to NT-proBNP <1000 pg/mL); **G**: CK (view limited to CK < 2000 U/L); **H**: lactate dehydrogenase (LDH) (U/L). The dashed lines correspond to the upper (U) and lower (L) limits of the reference range. The red line indicates the evolution trend of the biomarker during follow-up according to the isotonic regression method.

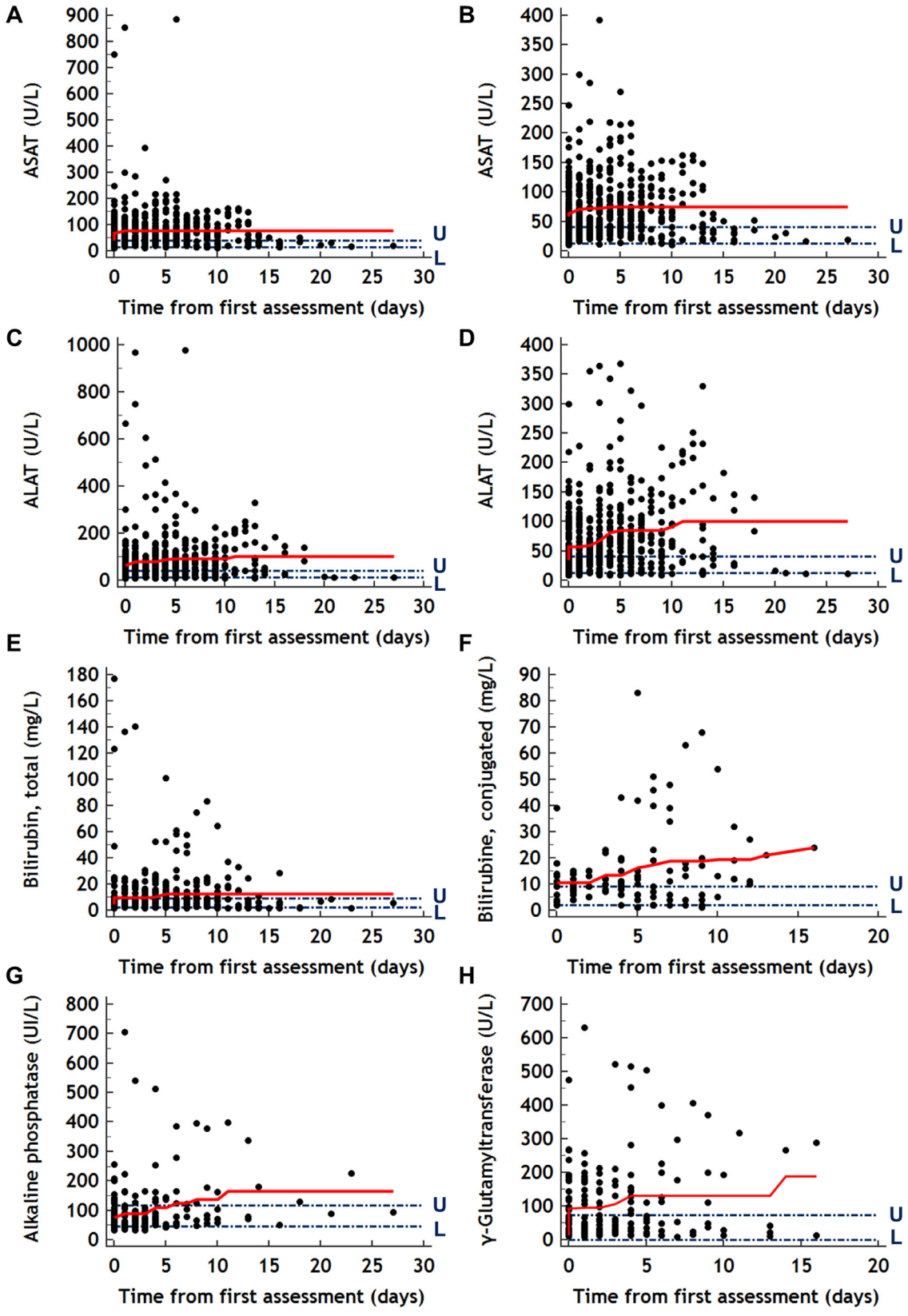

Fig. 3. *Kinetics over time of the most frequently observed biochemical abnormalities during the follow-up of patients with severe COVID-19 (part 3)*: **A**: aspartate aminotransferases (ASAT) (U/L); **B**: ASAT (U/L) (view limited to ASAT <400 U/L); **C**: alanine aminotransferases (ALAT) (U/L); **D**: ALAT (U/L) (view limited to ALAT <400 U/L); **E**: bilirubin, total (mg/L); **F**: bilirubin, conjugated (mg/L); **G**: alkaline phosphatase (UI/L); **H**: γ-glutamyltransferase (U/L). The red line indicates the evolution trend of the biomarker during follow-up according to the isotonic regression method.

Table 4
Association between biochemical abnormalities and the occurrence of acute respiratory failure or in-hospital mortality among patients with severe COVID-19 in the multivariable multilevel analysis.

Acute respiratory failure, model #1: Urea nitrogen, C-reactive protein, age, gender, medical history[a]

Variables	Estimation	Standard error	Odds ratio, adjusted (95% CI)	*P*-value[b]
C-reactive protein > 90 mg/L	1·93	0·55	6·87 (2·36–20·01)	<0·001
Medical history of type 2 diabetes	1·50	0·73	4·49 (1·07–18·89)	0·04
Urea nitrogen > 0·36 g/L	1·36	0·63	3·91 (1·15–13·29)	0·03
Age	0·03	0·02	1·03 (0·99–1·07)	0·18
Male gender	0·92	0·67	2·51 (0·68–9·24)	0·17
Medical history of dyslipidemia	0·86	0·82	2·36 (0·47–11·78)	0·30

Acute respiratory failure, model #2: Creatinine, C-reactive protein, age, gender, medical history[a]

Variable	Estimation	Standard error	Odds ratio, adjusted (95% CI)	*P*-value[b]
C-reactive protein > 90 mg/L	1·93	0·54	6·90 (2·38–20·01)	<0·001
Medical history of type 2 diabetes	1·45	0·73	4·26 (1·02–17·90)	0·049
Male gender	1·15	0·67	3·16 (0·86–11·69)	0·09
Age	0·01	0·02	1·01 (0·98–1·05)	0·52
Creatinine >9·7 mg/L	0·33	0·60	1·39 (0·43–4·49)	0·58
Medical history of dyslipidemia	0·71	0·81	2·04 (0·41–10·00)	0·38

In-hospital mortality, Model: Urea nitrogen, age, gender, medical history

Variable	Estimation	Standard error	Odds ratio, adjusted (95% CI)	*P*-value[b]
Age	0·12	0·04	1·12 (1·03–1·22)	0·006
Medical history of COPD	2·64	1·31	14·06 (1·08–182·74)	0·04
Male gender	1·90	1·06	6·70 (0·83–53·87)	0·07
Urea nitrogen >0·42 g/L	1·29	0·84	3·64 (0·71–18·71)	0·12
Medical history of type 2 diabetes	1·35	0·97	3·85 (0·57–25·97)	0·17
Medical history of cardiovascular disease	1·04	0·98	2·82 (0·41–19·31)	0·29

Note. COPD: chronic obstructive pulmonary disease; 95% CI: 95% confidence interval.
[a] Patients' medical histories were selected to avoid multicollinearity regarding the endpoint.
[b] Two-level hierarchical logistic model (HLM), using the predictive quasi-likelihood method.

Table 5
Biochemical markers associated with in-hospital mortality among patients with severe COVID-19 disease in bivariate analyses.

Biological variable	n	ROC, *P*-value[a]	AUROC[a]	ROC-defined cut-off	Time-series analysis *P*-value[b]	Percentage of time according to the threshold (95% CI), No death	Percentage of time according to the threshold (95% CI), Death
Sodium (mmol/L)	854	0·77	0·510 (0·444–0·577)	—	—	—	—
Potassium (mmol/L)	854	0·07[c]	0·557 (0·494–0·618)	—	—	—	—
Chloride (mmol/L)	799	0·85	0·506 (0·444–0·569)	—	—	—	—
Urea nitrogen (g/L)	844	<0·001	0·597 (0·540–0·651)	>0·42	0·002	31·1 (23·8–38·3)	60·8 (41·2–80·4)
Creatinine (mg/L)	845	0·25	0·541 (0·468–0·611)	—	—	—	—
Hemoglobin (g/dL)	787	0·11	0·557 (0·488–0·626)	—	—	—	—
pH	785	<0·001	0·683 (0·618–0·743)	≤7·43	0·24	30·1 (23·2–36·9)	44·9 (23–66·8)
PO_2 (mm/Hg)	785	0·31	0·539 (0·464–0·615)	—	—	—	—
PCO_2 (mmHg)	785	0·04[c]	0·585 (0·501–0·663)	—	—	—	—
Bicarbonate (HCO_3^-) (mmol/L)	762	0·10	0·570 (0·483–0·652)	—	—	—	—
Lactates (mmol/L)	715	<0·001	0·677 (0·606–0·738)	>1·3	0·27	25·7 (18·6–32·8)	37·7 (16·2–59·1)
ASAT (U/L)	492	0·28	0·546 (0·461–0·630)	—	—	—	—
ALAT (U/L)	491	0·03[c]	0·587 (0·504–0·663)	—	—	—	—
Bilirubin, total (mg/L)	466	0·53	0·527 (0·440–0·609)	—	—	—	—
Total proteins (g/L)	744	0·002	0·614 (0·541–0·686)	≤56	0·44	16·9 (11·5–22·2)	26·6 (6·8–46·4)
C-reactive protein (mg/L)	388	0·06[c]	0·580 (0·491–0·658)	—	—	—	—
Calcium (mg/L)	266	0·54	0·537 (0·416–0·654)	—	—	—	—
Phosphorus (mg/L)	299	0·045[c]	0·606 (0·497–0·705)	—	—	—	—
hs-c Troponin I (pg/mL)	255	<0·001	0·737 (0·613–0·833)	>40	0·90	18·2 (10·4–25·9)	18·3 (0–45·5)
CK (U/L)	272	0·03[c]	0·617 (0·508–0·714)	—	—	—	—

Note. ALAT: alanine aminotransferases; ASAT: aspartate aminotransferases; AUROC: area under the receiver operating characteristic curve; CK: creatine kinase; hs-c Troponin I: high-sensitivity cardiac troponin I; PCO_2: partial pressure of carbon dioxide; PO_2: partial pressure of oxygen; ROC: receiver operating characteristics.
[a] Receiver operating characteristic (ROC) analysis, according to DeLong et al. with Bias-corrected and accelerated (BCa)-bootstrap interval after 10,000 iterations for the Youden index.
[b] Time-series analysis using a non-parametric test.
[c] Nominal *P*-values did not maintain their significance after Bonferroni correction.

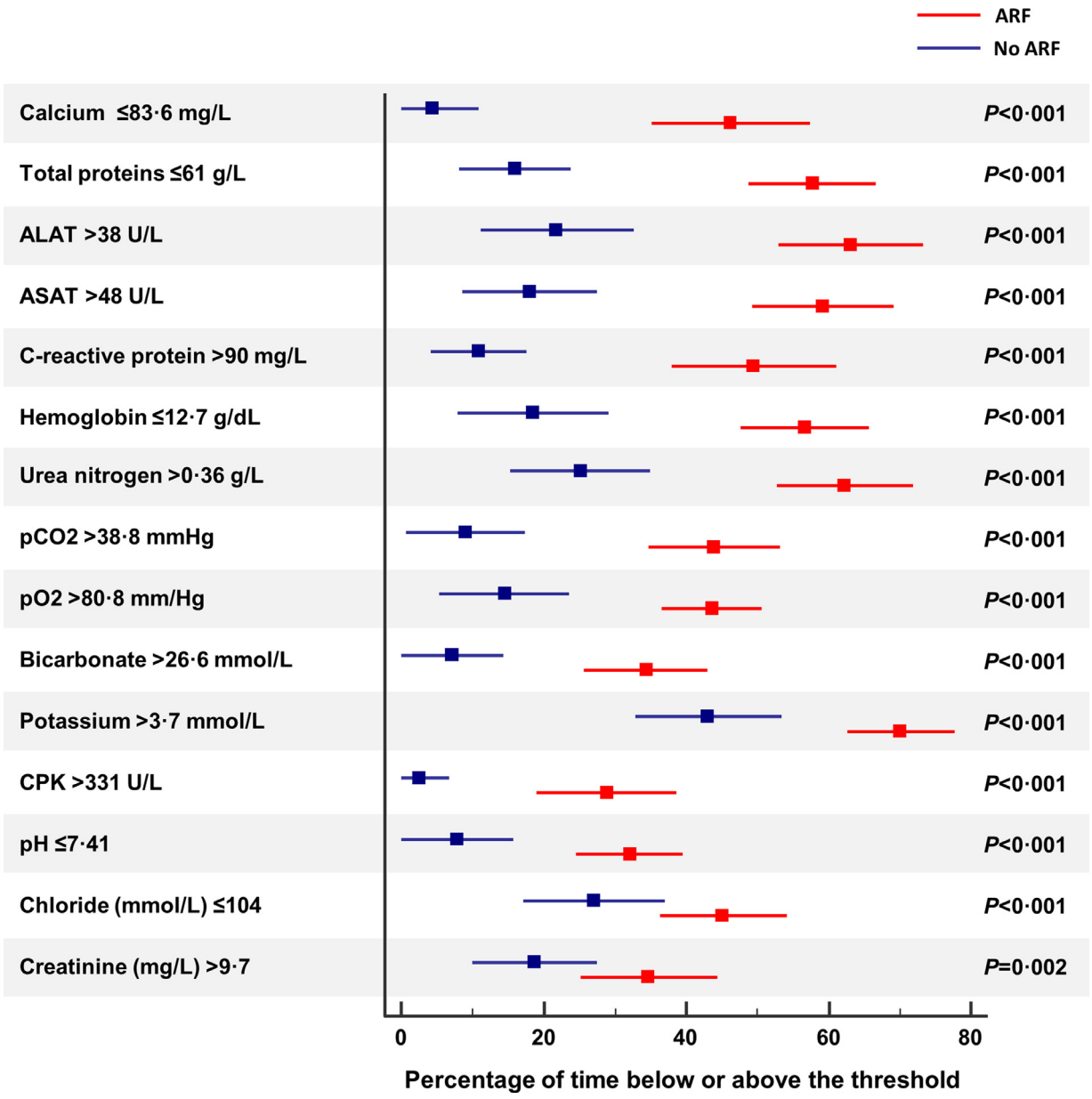

Fig. 4. Biochemical abnormalities associated with the occurrence of acute respiratory failure (ARF) among patients with severe COVID-19. A set of 20 biochemical markers with at least 250 iterations was systematically screened for the association with the occurrence of ARF using ROC analysis. All markers with a statistically significant ROC-defined threshold were assessed using time series analysis to calculate the percentage of time below or above the defined threshold. The calculated summary effects are reported as percentages of the total time of observation with the 95% CI, as noted in the Forest plot.

hypotheses for the occurrence of acute renal damage is the inadequacy of the inflammatory response linked to the cytokine storm observed in severe forms of COVID-19 and their effect on hypoperfusion of renal tubules [30]. A recent study reported that patients with severe COVID-19 have a high risk of developing Fanconi syndrome, leading to potentially life-threatening plasma disturbances [31]. SARS-CoV-2 infects the cells through its binding to the membrane-bound form of receptor-angiotensin converting enzyme II (ACE2) and subsequent internalization of the complex by the host cell [1,32-34]. There is emerging evidence about the direct cytopathic effect of SARS-CoV-2 since the cell entry receptor ACE2 is expressed on podocytes and tubule epithelial cells [30]. In line with these data, we observed a biphasic evolution of the phosphorus level in the blood of patients with severe COVID-19 with an initial decrease during the first four days, followed by a progressive increase that mirrored the degradation of kidney function. This evolution may reflect a direct cytotoxic effect of the virus with initial involvement of tubule epithelial cells, which is responsible for a phosphorus leakage in the urine and, in a second step, a glomerular attack, explaining the progressive increase in urea nitrogen and creatinine as well as phosphorus. These data are corroborated by the progressive increase in the proportion of patients with stage 3 AKI during the follow-up. In our study, patients with ARF and those who die form COVID-19 share the same pattern of urea nitrogen alteration. In addition to pulmonary involvement, renal involvement leads to life-threatening alterations in homeostatic regulatory processes. Further studies should address the significance of acute kidney injury in the prediction of COVID-19 related death and plead for long-term follow-up by a nephrologist of patients with severe COVID-19.

The ACE2 protein is highly expressed in the gastrointestinal tract, notably in the duodenum and the small intestine, gallbladder, testis, seminal vesicle, and adrenal gland [35]. A recent study also confirmed the expression of the ACE2 protein in human myocardial pericytes [36]. We can hypothesize that the direct cytopathic effect of SARS-

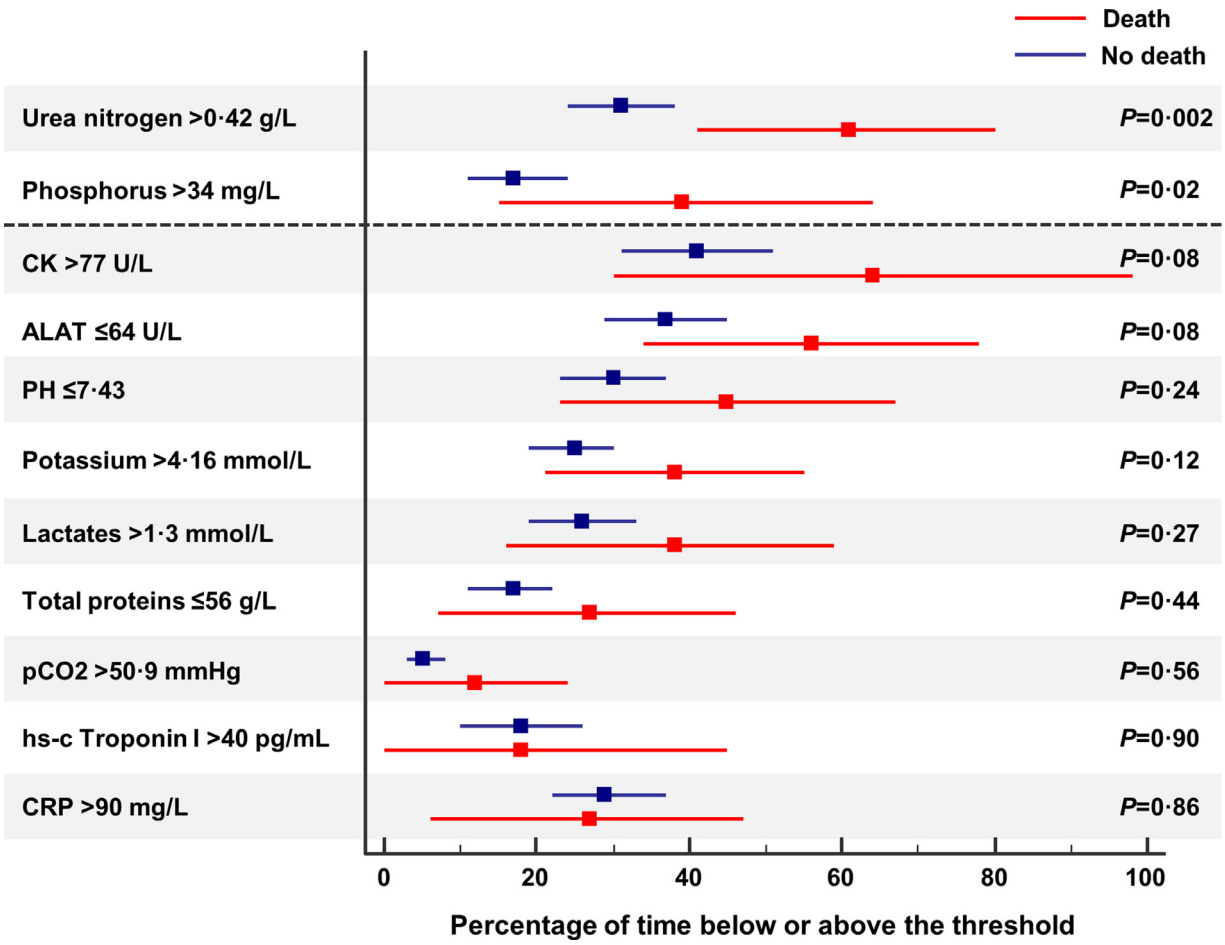

Fig. 5. Biochemical abnormalities associated with the occurrence of in-hospital mortality among patients with severe COVID-19. A set of 20 biochemical markers with at least 250 iterations was systematically screened for the association with the occurrence of in-hospital mortality using ROC analysis. All markers with a statistically significant ROC-defined threshold were assessed using time series analysis to calculate the percentage of time below or above the defined threshold. The calculated summary effects are reported as percentages of the total time of observation with the 95% CI, as noted in the Forest plot.

CoV-2 on pericytes may result in endothelial cell and microvascular dysfunction [36]. A retrospective single-center case series of 187 patients with COVID-19 from China showed that myocardial injury was significantly associated with the risk of death [37].

To date, descriptive data on COVID-19 did not report obvious cholestasis in patients with severe forms [38,39]. In our series, we have reported cholestatic involvement with conjugated hyperbilirubinemia and cytolysis over 30% of the observation time. These results raise the possibility of a direct toxic effect of the virus on the biliary epithelium, especially given the high level of expression of the ACE2 protein in the biliary tissue [35]. Long term evolution of these cholestatic syndromes deserves further studies, notably regarding the risk of cholestatic liver disease. The present study provides new data on the elevation of lipase levels among patients with severe COVID-19. This elevation could be related to several mechanisms, other than direct pancreatic involvement, and include intestinal disease, acidosis, or the presence of shock. We have observed elevations in CK and LDH that have also been reported in the literature [8,38,40-42].

We acknowledge several potential limitations of the study that should be considered in the interpretation of our findings. Although we have studied an extensive follow-up dataset, our study is based on a relatively small number of patients, and our results need to be confirmed in independent studies. Nevertheless, we have systematically included all consecutive patients with newly diagnosed severe COVID-19, which allowed us to describe the biochemical abnormalities on a homogeneous population. The study design is retrospective; nevertheless, we used data from a structured and prospectively maintained database [14]. In our study, the follow-up of patients was relatively short, which could lead to an underestimation of the risk of COVID-19 related mortality. Patients with severe COVID-19 can exhibit immunological determinants of a cytokine storm [42-45], notably with high levels of CXCL10, CCL7, and IL-1 receptor antagonist, and which could influence the risk of lung injury and fatal outcome [45]. In our study, IL-6 and procalcitonin —an indirect marker of innate immunity— were not tested enough in patients to be assessed in the analysis. Our study has several strengths. First, we report an exhaustive description of the biochemical abnormalities and their kinetics over time among patients with severe COVID-19. Second, we assessed the relationship between the variation over time in biochemical markers and the occurrence of disease-related complications through a multilevel modeling approach adapted for repeated measures. Third, we studied a wide range of biochemical markers relating to both blood and urine and targeting several organs and vital functions. We notably highlighted a potentially strong association between acute kidney injury, the development of severe kidney damage, and their association with COVID-19 related in-hospital mortality.

In conclusion, in this retrospective, longitudinal cohort study, using an extensive biochemical dataset of serial data and time-series design on consecutive patients with newly diagnosed severe COVID-19, the follow-up of biochemical biomarkers kinetics was consistent with a severe multi-organ involvement along with a severe acute inflammatory response. High levels of CRP and urea nitrogen were potential predictors of ARF among patients with severe COVID-19.

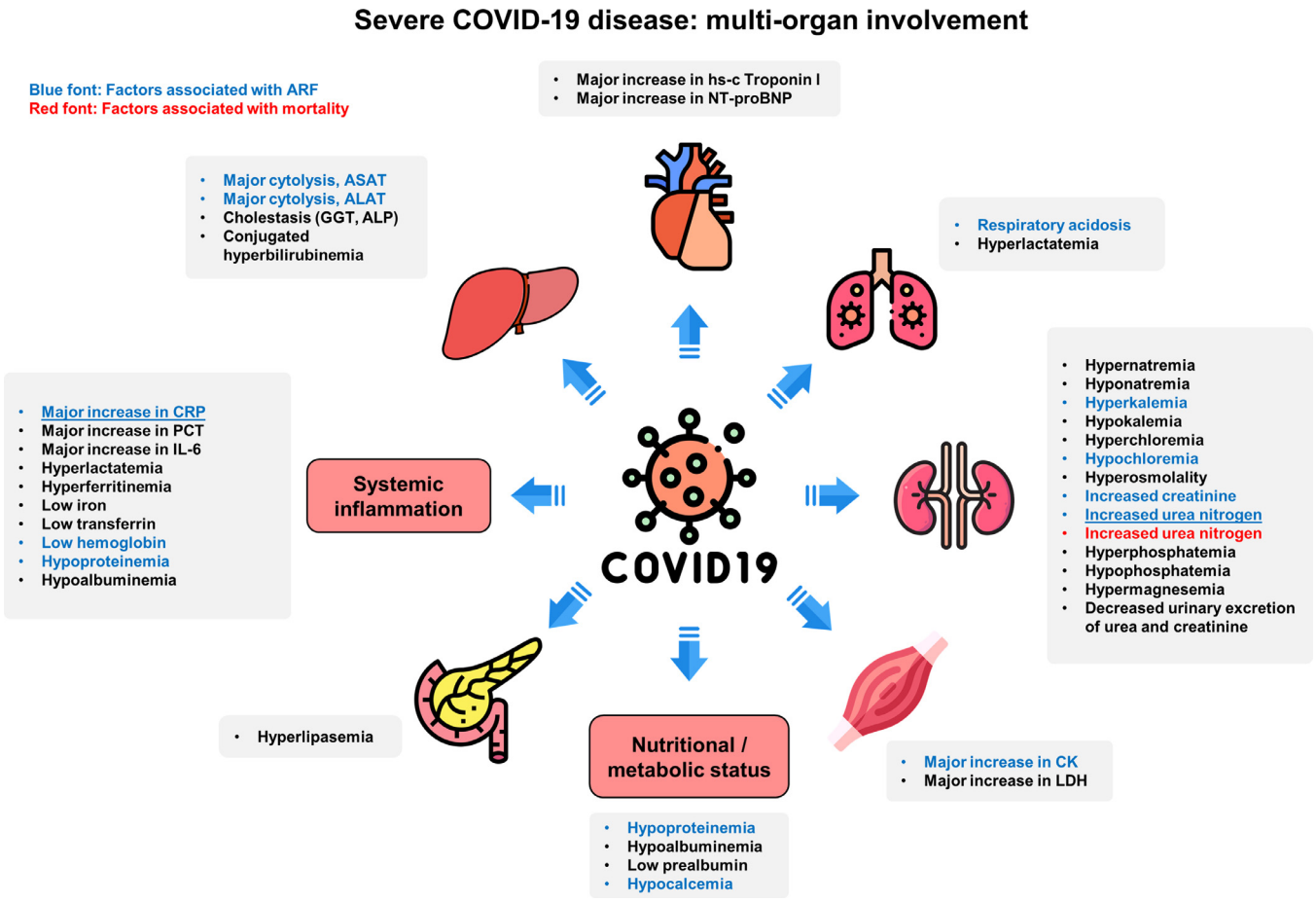

Fig. 6. Overview of the evolution of the main biochemical abnormalities and potential predictors acute respiratory failure (ARF) or in-hospital mortality among patients with severe COVID-19. Predictors of ARF in bivariate analyses are highlighted in blue font. Predictors of COVID-19 related mortality in bivariate analyses are highlighted in red font. Independent predictors of ARF in the multivariable multilevel analysis are underlined. ALP: alkaline phosphatase; ASAT: aspartate aminotransferases; ALAT: alanine aminotransferases; CK: creatine kinase; CRP: C-reactive protein; GGT: γ-glutamyltransferase; hs-c Troponin I: high-sensitivity cardiac troponin I; IL-6: interleukin 6; LDH: lactate dehydrogenase; NT-pro-BNP: N-Terminal pro-Brain Natriuretic Peptide; PCT: procalcitonin; (icons made by flaticon, flaticon.com; CC-BY-3.0).

Further studies should address the significance of acute kidney failure in the prediction of COVID-19 related death. Our results open new perspectives on the understanding of the pathophysiological mechanisms related to disease decompensation and multi-organ dysfunction that targets kidney function in the setting of severe COVID-19.

Declaration of Interest

The authors who have taken part in this study declare that they do not have anything to disclose regarding conflicts of interest concerning this manuscript.

Data sharing statement

Anonymized patient data are available for use in collaborative studies to researchers upon reasonable request (abderrahim.oussalah@univ-lorraine.fr). Data will be provided following the review and approval of a research proposal (including a statistical analysis plan) and completion of a data-sharing agreement. Responses to the request for the raw data will be judged by the IRB of the University Hospital of Nancy.

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Authors' contributions

AO: has full access to all the data in this study and take full responsibility as the guarantor for the integrity of the data and the accuracy of the data analysis, study concept, laboratory diagnostic assessment, literature review, data synthesis and statistical analysis, drafting/revision of the manuscript, analysis and interpretation of data, approved the final draft, final responsibility for the decision to submit for publication; **SG**: laboratory diagnostic assessment, data extraction, analysis and interpretation of data, approved the final draft; **ICU**: data synthesis and statistical analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **EL**: data extraction, analysis and interpretation of data, approved the final draft; **FB**: laboratory diagnostic assessment, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **SO**: laboratory diagnostic assessment, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **CM**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **IAG**: laboratory diagnostic assessment, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **BMC**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **MM**: analysis and interpretation of data, approved the final draft; **EJ**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **RK**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **JLO**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **RM-GR**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **FN**: laboratory diagnostic assessment, analysis and interpretation of data, approved the final draft; **SB**: management of patients, analysis and interpretation of data, approved the final draft; **NT**: data synthesis and statistical analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **MRL**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **AK**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **LF**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **BL**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **SG**: management of patients, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **ES**: laboratory diagnostic assessment, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft; **JLG**: study concept, laboratory diagnostic assessment, analysis and interpretation of data, drafting/revision of the manuscript, approved the final draft.

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Supplementary materials

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