Hyperoxemia and excess oxygen use in early acute respiratory distress syndrome: insights from the LUNG SAFE study

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Abstract

Background: Concerns exist regarding the prevalence and impact of unnecessary oxygen use in patients with acute respiratory distress syndrome (ARDS). We examined this issue in patients with ARDS enrolled in the Large observational study to UNderstand the Global impact of Severe Acute respiratory Failure (LUNG SAFE) study.

Methods: In this secondary analysis of the LUNG SAFE study, we wished to determine the prevalence and the outcomes associated with hyperoxemia on day 1, sustained hyperoxemia, and excessive oxygen use in patients with early ARDS. Patients who fulfilled criteria of ARDS on day 1 and day 2 of acute hypoxic respiratory failure were categorized based on the presence of hyperoxemia (PaO₂ > 100 mmHg) on day 1, sustained (i.e., present on day 1 and day 2) hyperoxemia, or excessive oxygen use (FiO₂ ≥ 0.60 during hyperoxemia).

Results: Of 2005 patients that met the inclusion criteria, 131 (6.5%) were hypoxemic (PaO₂ < 55 mmHg), 607 (30%) had hyperoxemia on day 1, and 250 (12%) had sustained hyperoxemia. Excess FiO₂ use occurred in 400 (66%) out of 607 patients with hyperoxemia. Excess FiO₂ use decreased from day 1 to day 2 of ARDS, with most hyperoxic patients on day 2 surviving relatively low FiO₂. Multivariate analyses found no independent relationship between day 1 hyperoxemia, sustained hyperoxemia, or excess FiO₂ use and adverse clinical outcomes. Mortality was 42% in patients with excess FiO₂ use, compared to 39% in a propensity-matched sample of normoxemic (PaO₂ 55–100 mmHg) patients (P = 0.47).

Conclusions: Hyperoxemia and excess oxygen use are both prevalent in early ARDS but are most often non-sustained. No relationship was found between hyperoxemia or excessive oxygen use and patient outcome in this cohort.

Trial registration: LUNG-SAFE is registered with ClinicalTrials.gov, NCT02010073

Keywords: Hyperoxia, Hypoxia, Hyperoxemia, Hypoxemia, Oxygen therapy, Acute respiratory distress syndrome, Mortality, Invasive mechanical ventilation
Key messages
- Hyperoxemia and excess FIO\textsubscript{2} use was prevalent in patients with early ARDS. Hyperoxemia occurred in 30\% of patients, while two thirds of these patients received excess oxygen therapy.
- While a similar proportion of patients were hyperoxemic on day 2 of ARDS, higher FIO\textsubscript{2} use did decrease. Consequently, most day 2 hyperoxemia was seen in patients at lower FIO\textsubscript{2}, in whom gas exchange was improving.
- In the majority of patients, both hyperoxemia and excess oxygen use were transient, although sustained hyperoxemia occurred in 12\% of patients.
- Higher FIO\textsubscript{2} use was independently associated with the risk of hyperoxemia, illustrating the need for close attention to oxygen use to reduce this risk.
- We found no relationship between the degree and duration of hyperoxemia or of excessive oxygen use, and outcome in early ARDS, in this patient cohort.

Background
Acute respiratory distress syndrome (ARDS) is a syndrome characterized by impaired gas exchange resulting in low oxygen tensions in the blood (i.e., hypoxemia) and tissues (i.e., hypoxia) [1]. Tissue hypoxia is harmful, leading to cell death, organ failure, and increased mortality in the critically ill [2]. While oxygen therapy can reverse tissue hypoxia, little evidence exists regarding the optimal use of oxygen in patients with ARDS. Critically ill patients frequently receive higher inspired oxygen concentrations than necessary [3], perhaps due to concerns regarding tissue hypoxia [4, 5].

Hyperoxemia and the resultant tissue hyperoxia may worsen systemic organ injury in the critically ill. Arterial hyperoxemia has been associated with increased mortality in some older [6–8] but not more recent [9, 10] studies of patients with acute brain injury. Hyperoxemia was associated with worse outcomes in cohort patients with acute ischemic stroke or subarachnoid/intracerebral hemorrhage that required invasive mechanical ventilation [11]. Supplemental oxygen therapy worsened myocardial injury and infarct size in patients post myocardial infarction [12]. In patients resuscitated post cardiac arrest, hyperoxia has been associated with harm in several [13–16] studies, although the most recent study [17] did not confirm this. Potential mechanisms of oxygen toxicity remain poorly understood and may include systemic arterial vasoconstriction [18, 19], and cytotoxic effects of reactive oxygen species [20–22]. In randomized trials, “induced” hyperoxemia (using 100\% oxygen) increased 28-day mortality in septic shock patients [23], while critically ill patients randomized to a target arterial oxygen tension (PaO\textsubscript{2}) of 70–100 mmHg had lower mortality compared to patients with a “conventional” target of PaO\textsubscript{2} up to 150 mmHg [24] in a single-center study. While a recent large international multicenter trial demonstrated no effect of conservative oxygen therapy in a diverse cohort of critically ill patients [25], a subsequent sub-study raised the possibility of clinically important harm with conservative oxygen therapy in patients with sepsis [26].

In ARDS, the relationship between oxygen use and outcome is complex. The severely impaired gas exchange means that high fraction of inspired oxygen (FIO\textsubscript{2}) use may simply reflect a more severe alveolar-arterial oxygen gradient and hence be a marker of ARDS severity. In mild ARDS, relatively modest levels of FIO\textsubscript{2} may result in (moderate) hyperoxemia and tissue hyperoxia. In addition, severe degrees of systemic hyperoxemia (i.e., PaO\textsubscript{2} > 300) associated with harm in other critically ill populations are not possible in ARDS. However, even moderate systemic hyperoxemia that may be more commonly seen in ARDS could be harmful [27]. Furthermore, the use of high FIO\textsubscript{2} can have direct toxic effects on the lung [28, 29], sensitize the lung to subsequent injury, adversely affect the lung innate immune response [30], and worsen ventilation-induced injury [31–33]. These complexities highlight the need to distinguish between hyperoxemia and high FIO\textsubscript{2} use. In patients receiving high FIO\textsubscript{2}, it is important to determine whether this was necessary to achieve normoxemia or if it could have been avoided (i.e., excess oxygen use).

We wished to examine the impact of hyperoxemia and of excess oxygen use in this secondary analysis of patients with ARDS in the LUNG SAFE patient cohort [34]. Our primary objective was to determine the prevalence of early and sustained hyperoxemia and of excess oxygen use in patients with hyperoxemia. Secondary objectives included identifying factors associated with hyperoxemia and with excess oxygen use and examining the relationship between hyperoxemia and excess oxygen use and outcomes from ARDS.

Methods
Design, setting, and participants
This is a sub-study of the LUNG SAFE study, an international, multicenter, prospective cohort study of patients receiving invasive or noninvasive ventilation, and the detailed methods and protocol have been published elsewhere [34]. In brief, LUNG SAFE was an international, multicenter, prospective cohort study, with a 4-week enrolment window in the winter season in both hemispheres [34]. National coordinators and site investigators obtained ethics committee approval and ensured data integrity and validity.

Given the study focus on early hyperoxemia and excess oxygen use, we restricted the study population to patients that fulfilled ARDS criteria within 48 h of ICU admission, and who remained in the ICU for at least 2 days from ARDS onset. Patients transferred from other
ICUs after 2 days, patients that developed ARDS later in their ICU stay, and patients that received early ECMO were excluded (Fig. 1). Additional methodological details are available in Additional file 1.

Data collection and analysis
All data were recorded for each patient at the same time each day within participating ICUs, normally as close as possible to 10 a.m. each day. Data on ventilatory settings were recorded simultaneously with arterial blood gas analysis. The following definitions were applied on day 1 and on day 2 of ARDS: hypoxemia (PaO₂ < 55 mmHg), normoxemia (PaO₂ 55–100 mmHg), and hyperoxemia (PaO₂ > 100 mmHg). Excess oxygen use was defined as the use of FIO₂ ≥ 0.6 in patients with hyperoxemia (PaO₂ > 100 mmHg). Patients with hyperoxemia on days 1 and 2 of ARDS were considered to have sustained hyperoxemia. Analogously, we also defined patients with sustained hypoxemia and sustained normoxemia.

The duration of invasive mechanical ventilation (MV) was calculated as the number of days between the date of intubation and the date of extubation in ICU (or death, if the patient died under invasive MV). Similarly, invasive ventilator-free days were calculated as the number of days from weaning from invasive MV to day 28, and for patients who died before weaning, we considered to have a ventilator-free-day value of 0. Patient survival was evaluated at hospital discharge, or at day 90, whichever occurred first. Our other data definitions have been previously reported [34–37].

Statistical analyses
Descriptive statistics included proportions for categorical and mean (standard deviation) or median (interquartile range) for continuous variables. No assumptions were made for missing data. To assess differences among three groups (systemic hypoxemia, normoxemia, and hyperoxemia), we performed chi-squared test (or Fisher exact test) for discrete variables and analysis of variance (ANOVA) (or Kruskal-Wallis test) for continuous variables. Bonferroni correction was applied to determine significance in the setting of multiple comparisons. Chi-square test (or Fisher exact test), Student’s t test (or Wilcoxon Mann Whitney test) were used to assess

Fig. 1 Flow chart describing criteria used to select and to classify the ARDS study population
differences between groups (i.e., sustained hyperoxemia and sustained normoxemia) in discrete and continuous distributions of parameters, respectively.

Locally estimated scatterplot smoothing (LOESS) method was used to inspect the relationship between mortality and PaO$_2$ and FIO$_2$ measured on day 1 and on day 2 of ARDS.

Multivariable logistic regression models were used to evaluate factors associated with the presence of either hyperoxemia or excess of oxygen use, and with mortality. In each regression model, the independent predictors (demographic characteristics and clinical parameters measured at the first day of ARDS) were identified through a stepwise regression approach. This approach combines forward and backward selection methods in an iterative procedure (with a significance level of 0.05 both for entry and retention) to select predictors in the final multivariable model. Results were reported as odds ratio (OR) with 95% confidence interval (CI).

Propensity score matching method was applied to evaluate the possible impact of sustained hyperoxemia on main outcomes (mortality, ventilation-free days, and duration of MV) in patients with mild-moderate ARDS. Patients with severe ARDS were excluded as there were no such patients in the sustained hyperoxemia group. In detail, patients with sustained hyperoxemia and sustained normoxemia were matched (1:1 match without replacement), using a caliper of 0.2 standard deviation of the logit of the propensity score, and the balance between the matched groups was assessed by the standardized differences of each independent variable used in the propensity score estimation. Statistical significance of the difference in continuous variables, as ventilation-free days and duration of MV, was evaluated with Wilcoxon signed-rank test, while for difference in proportions of deaths, we applied McNemar’s test. Survival probability in these matched groups was estimated using the Kaplan-Meier approach and assuming that patients discharged alive from hospital before 90 days were alive on day 90. Statistical difference between survival curves was assessed through Kein and Moeschberger test. The same approach was used to assess the possible impact of excess use of oxygen on main outcomes.

All p values were two-sided, with p values < 0.05 considered as statistically significant. Statistical analyses were performed with R, version 3.5.2. (R Project for

![Fig. 2](https://example.com/fig2.png) **Fig. 2** Arterial oxygen tensions and use of oxygen in patients on days 1 and 2 of ARDS. **a** The distribution of PaO$_2$ on day 1 of ARDS, demonstrating a wide range of PaO$_2$. **b** Density distributions of PaO$_2$ on days 1 (red line) and day 2 (blue line) of ARDS. **c** Histogram of FIO$_2$ and PaO$_2$ on day 1 of ARDS. **d** Histogram of FIO$_2$ and PaO$_2$ on day 2 of ARDS. Note: in **c** and **d**, each bar is segmented into hyperoxemia (black), normoxemia (dark gray), hypoxemia (light gray), and unknown (white) component.
| Parameter                                      | Hypoxemia (PaO₂ < 55 mmHg) | Normoxemia (55 mmHg ≤ PaO₂ ≤ 100 mmHg) | Hyperoxemia (PaO₂ > 100 mmHg) | p value (among groups) |
|------------------------------------------------|----------------------------|----------------------------------------|------------------------------|------------------------|
| N (%)                                          | 131 (6.53)                 | 1267 (63.19)                           | 607 (30.27)                  |                        |
| Male, n (%)                                     | 73 (55.73)                 | 796 (62.83)                            | 359 (59.14)                  | 0.1259                 |
| Age (years), mean ± SD                         | 59.20 ± 16.86              | 62.21 ± 16.74                          | 61.88 ± 16.82                | 0.1264                 |
| BMI (kg/m²), mean ± SD                         | 27.23 ± 6.82               | 27.66 ± 8.26                           | 26.90 ± 6.84                 | 0.5646                 |
| ARDS risk factors, n (%)                       |                            |                                        |                              |                        |
| None                                           | 9 (6.87)                   | 103 (8.13)                             | 52 (8.57)                    | 0.8088                 |
| Only non-pulmonary                             | 15 (11.45)                 | 229 (18.07)                            | 106 (17.46)                  | 0.1641                 |
| Only pulmonary                                 | 92 (70.23)                 | 769 (60.62)                            | 357 (58.81)                  | 0.0525                 |
| Both                                           | 15 (11.45)                 | 167 (13.18)                            | 92 (15.16)                   | 0.3789                 |
| Illness severity at ARDS onset                  |                            |                                        |                              |                        |
| PaO₂ (mmHg), mean ± SD                         | 47.1 ± 6.2                 | 76.8 ± 11.9*                           | 137.8 ± 41.0*                | < 0.0001               |
| PaO₂/FIO₂ (mmHg), mean ± SD                    | 75.12 ± 38.97              | 140.49 ± 56.70*                        | 205.90 ± 54.88*              | < 0.0001               |
| SpO₂ (%), median (q₁–q₃)                       | 88 (82–94)                 | 95 (92–97)*                            | 98 (97–99)*                  | < 0.0001               |
| ARDS severity, n (%)                           |                            |                                        |                              |                        |
| Mild                                           | 4 (3.05)                   | 205 (16.18)*                           | 330 (54.37)*                 | < 0.0001               |
| Moderate                                       | 22 (16.79)                 | 683 (53.91)*                           | 273 (33.98)*                 | < 0.0001               |
| Severe                                         | 105 (80.15)                | 379 (29.91)*                           | 4 (0.66)*                    | < 0.0001               |
| P₆CO₂ (mmHg), mean ± SD                        | 54.3 ± 25.0                | 46.3 ± 15.3*                           | 44.8 ± 14.6*                 | 0.0031                 |
| pH, mean ± SD                                  | 7.31 ± 0.15                | 7.33 ± 0.12                            | 7.32 ± 0.13                  | 0.7446                 |
| Bicarbonate (mmol/L), mean ± SD                | 26.3 ± 10.9                | 23.3 ± 6.5                             | 22.3 ± 6.3*                  | < 0.0001               |
| Base excess (mEq/L), mean ± SD                 | 0.5 ± 10.8                 | −2.0 ± 6.8                             | −3.1 ± 6.8*                  | 0.0001                 |
| Non-respiratory SOFA score adjusted, mean ± SD | 6.14 ± 4.15                | 6.08 ± 3.94                            | 6.28 ± 4.00                  | 0.6246                 |
| SOFA score adjusted, mean ± SD                | 10.25 ± 4.20               | 9.51 ± 3.98                            | 8.87 ± 3.93*                 | 0.0005                 |
| Respiration                                    | 3.79 ± 0.46                | 3.15 ± 0.66                            | 2.45 ± 0.50                  | < 0.0001               |
| Central nervous system                         | 1.68 ± 1.72                | 1.74 ± 1.66                            | 1.92 ± 1.69                  | 0.1161                 |
| Cardiovascular                                 | 1.77 ± 1.74                | 2.03 ± 1.76                            | 1.93 ± 1.74                  | 0.1760                 |
| Liver                                          | 0.65 ± 0.98                | 0.54 ± 0.96                            | 0.51 ± 0.92                  | 0.2855                 |
| Coagulation                                    | 1.20 ± 1.45                | 0.95 ± 1.31                            | 0.98 ± 1.34                  | 0.1751                 |
| Renal                                          | 0.69 ± 1.04                | 1.77 ± 1.10                            | 0.88 ± 1.22                  | 0.3333                 |
| Pressor support infusion rates                 |                            |                                        |                              |                        |
| Dopamine (µg/kg/min), mean ± SD                | 8.19 ± 6.94                | 8.58 ± 5.02                            | 7.73 ± 5.98                  | 0.4151                 |
| Dobutamine (µg/kg/min), mean ± SD              | 5.52 ± 3.74                | 5.72 ± 4.05                            | 6.75 ± 3.53                  | 0.3565                 |
| Noradrenaline (µg/kg/min), mean ± SD           | 0.50 ± 0.67                | 0.45 ± 0.75                            | 0.54 ± 1.48                  | 0.6701                 |
| Adrenaline (µg/kg/min), mean ± SD              | 1.10 ± 2.03                | 0.48 ± 0.69                            | 0.43 ± 0.55                  | 0.8434                 |
| Management factors at ARDS onset               |                            |                                        |                              |                        |
| Invasive mechanical ventilation, n (%)         | 102 (77.86)                | 1000 (78.93)                           | 506 (83.36)                  | 0.0619                 |
| Control mode of ventilation, mean ± SD         | 70 (54.69)                 | 693 (55.89)                            | 386 (64.23)*                 | 0.0021                 |
| FIO₂, median (q₁–q₃)                           | 0.80 (0.50–1.00)           | 0.60 (0.41–0.80)*                      | 0.65 (0.50–1.00)*            | < 0.0001               |
| FIO₂ ≥ 0.6, n (%)                              | 90 (68.70)                 | 670 (52.88)*                           | 400 (65.90)*                 | < 0.0001               |
| FIO₂ ≥ 0.6 at 2nd day, n (%)                   | 64 (73.56)                 | 372 (57.94)*                           | 167 (43.60)*                 | < 0.0001               |
| Tidal volume (ml/kg), mean ± SD                | 7.9 ± 2.2                  | 7.8 ± 2.0                              | 7.9 ± 2.0                    | 0.2256                 |
| PEEP (cmH₂O), mean ± SD                        | 8.7 ± 3.3                  | 8.1 ± 3.2                              | 7.9 ± 3.1*                   | 0.0174                 |
| PIP (cmH₂O), mean ± SD                         | 25.7 ± 8.90                | 25.3 ± 8.5                             | 25.6 ± 8.7                   | 0.6295                 |
Table 1 Characteristics of study population (n = 2005), stratified by arterial oxygenation on day 1 (Continued)

| Parameter | Hypoxemia (PaO2 < 55 mmHg) | Normoxemia (55 mmHg ≤ PaO2 ≤ 100 mmHg) | Hyperoxemia (PaO2 > 100 mmHg) | p value (among groups) |
|-----------|---------------------------|------------------------------------------|-------------------------------|-----------------------|
| Dynamic compliance (ml/cmH2O), mean ± SD | 39.0 ± 38.4 | 36.9 ± 37.8 | 35.6 ± 38.9 | 0.7759 |
| Total respiratory rate (breaths/min), mean ± SD | 23.2 ± 7.1 | 21.9 ± 6.9 | 21.1 ± 7.0 | 0.0003 |
| Standardized minute ventilation (l/min), mean ± SD | 14.4 ± 7.8 | 11.4 ± 5.3* | 10.8 ± 5.0† | < 0.0001 |
| Patients in whom plateau pressure measured, n (%) | 24 (18.32) | 304 (23.99) | 186 (30.64) | 0.0012 |
| Plateau pressure (cmH2O), mean ± SD | 24.3 ± 9.0 | 23.4 ± 6.1 | 23.0 ± 5.6 | 0.7512 |
| Driving pressure (cmH2O), mean ± SD | 16.0 ± 8.2 | 14.6 ± 5.4 | 15.0 ± 5.2 | 0.4941 |

Clinical outcomes

Hospital mortality (90 days), n (%) | 47 (35.88) | 486 (38.54) | 227 (37.52) | 0.7934 |

Ventilation free days (days), median (q1–q3) | All | 10.0 (0.0–22.0) | 12.0 (0.0–23.0) | 16.0 (0.0–24.0)† | 0.0303 |
Survivors at ICU discharge | 20.0 (14.0–24.0) | 21.0 (15.0–25.0) | 23.0 (18.0–26.0)‡ | 0.0002 |

Duration mechanical ventilation (days), median (q1–q3) | All | 7.0 (4.0–13.0) | 8.0 (4.0–15.0) | 7.0 (3.0–13.0)† | 0.0074 |
Survivors at ICU discharge | 9.0 (5.0–15.0) | 8.0 (4.0–14.0) | 6.0 (3.0–11.0)‡ | 0.0002 |

Abbreviations: ARDS acute respiratory distress syndrome, BMI body mass index, COPD chronic obstructive pulmonary disease, FIO2 fraction of inspired oxygen, PaO2 arterial oxygen partial pressure, PIP peak inspiratory pressure, PEEP positive end-expiratory pressure, q1 first quartile, q3 third quartile, SOFA sepsis-related organ failure assessment, SD standard deviation, SpO2 peripheral oxygen saturation

*Plateau pressure and driving pressure values are limited to patients in whom this value was reported and in whom either an assist control mode was used or in whom a mode permitting spontaneous ventilation was used and where the set and total respiratory rates were equal. Patients receiving HFOV or ECMO were also excluded
†Percentage was calculated on patients with FIO2 available during the second day and with FIO2 ≥ 0.60 at day 1
‡p value < 0.05 (Bonferroni’s correction), comparison with “Hypoxemia” group

Results

Of 4499 patients that developed AHRF in the LUNG SAFE cohort, 2127 of these developed ARDS within 2 days of ICU admission, of whom 2052 remained in ICU for at least 2 days from ARDS onset. The study population consists of 2005 of these patients that did not receive ECMO (Fig. 1).

Systemic oxygen tensions

In the study population, 607 subjects (30%) were hyperoxic, while 6.5% of patients remained hypoxic, on day 1 of ARDS (Fig. 2a, Table 1, eTable 1). Density distributions of arterial oxygen tension on days 1 and 2 of ARDS (Fig. 2b) reveal similar PaO2 profiles for days 1 and 2. In the hyperoxic population at day 1, 59% had a transient hyperoxemia, while in 250 (41%) patients, the condition was sustained, with PaO2 > 100 mmHg on both the first and second day of ARDS (Fig. 1; eTable 2). All eTables are included in Additional file 1.

A multivariable analysis of factors independently associated with day 1 hyperoxemia identified higher FIO2 use, lower PEEP, lower respiratory rate, a lower sepsis-related organ failure assessment (SOFA) cardiovascular score, and comorbidities such as neoplasm and/or immunosuppression and heart failure (Table 2).

Use of oxygen

FIO2 use varied widely across the spectrum of PaO2 on day 1 of ARDS (Fig. 2c). In patients that received a FIO2 greater than 0.9 (459 patients), 11% had systemic hypoxemia, while 38% had hyperoxemia (Fig. 2c). Median PaO2 was similar across deciles of FIO2 (Fig. 3a). On day 2 of ARDS, the proportions of patients receiving higher FIO2 decreased, although around one third of patients were hyperoxic at each decile of FIO2 (Figs. 2d and 3b, c). In contrast, 40% (57/131) of patients with hypoxemia on day 1 received a FIO2 of 0.5 or less. Median FIO2 decreased between day 1 and day 2 in patients with hyperoxemia, normoxemia, and hypoxemia (Fig. 3b), although median PaO2 remained similar across deciles of FIO2 on day 2 (Fig. 3c).

Excess oxygen use was seen in 400 patients, comprising 66% of all patients with hyperoxemia, on day 1 of ARDS (Table 1). In 315 patients (79%), excess oxygen use was transient, while in 85 (21%) patients, excess oxygen use was also seen on day 2 of ARDS. In multivariable analysis, factors independently associated with excess oxygen use included lower PaO2/FIO2 ratio,
higher PEEP, higher tidal volume, and chronic renal failure (Table 2).

Hyperoxemia, excess oxygen use, and outcome
On day 1, LOESS demonstrated the relationship between unadjusted mortality risk and PaO₂ was relatively flat over the range of PaO₂ (Fig. 4a). On day 2, the unadjusted risk of hospital mortality increased in patients with systemic hypoxemia (Fig. 4b). LOESS in non-hypoxemic patients demonstrated that unadjusted mortality risk increased with increasing FIO₂ on both days 1 and 2 (Fig. 4c, d).

Multivariate analyses found no independent association between day 1 systemic oxygen tension or inspired oxygen concentration and outcome, in either the full study population or in the subset of patients with hyperoxemia (Table 3).

In a propensity-matched analysis (n = 448), no outcome differences were found in patients with sustained hyperoxemia compared to matched sustained normoxemia patients (Fig. 5a; eTable 3). Similarly, mortality in patients with hyperoxemia and excess oxygen use (42%) was not different to that in patients with normoxemia (39%, P = 0.47) in a propensity-matched sample (n = 666) (Fig. 5b; eTable 4).

Discussion
Our findings demonstrate that hyperoxemia and excess FIO₂ use was prevalent in patients with early ARDS in patients enrolled in the LUNG SAFE cohort. Hyperoxemia occurred in 30% of patients, while two thirds of these patients received excess oxygen therapy. While a similar proportion of patients was hyperoxic on day 2 of ARDS, higher FIO₂ use did decrease. Consequently, most day 2 hyperoxemia was seen in patients at lower FIO₂, in whom gas exchange was improving. In the majority of patients, both hyperoxemia and excess oxygen use were transient, although sustained hyperoxemia occurred in 12% of patients. Higher FIO₂ use was independently associated with the risk of hyperoxemia, illustrating the need for close attention to oxygen use to reduce this risk. We found no relationship between the degree and duration of hyperoxemia or of excessive

| Parameter                                      | Odds ratio (95% confidence interval) | p value |
|------------------------------------------------|--------------------------------------|---------|
| Outcome—hyperoxemia at day 1 (model° on 1855 patients) |                                      |         |
| FIO₂ (0.1 unit)                                 | 1.168 (1.115; 1.224)                 | < .0001 |
| Bicarbonate (mmol/L)                           | 0.967 (0.951; 0.984)                 | < .0001 |
| Total respiratory rate (breath/min)            | 0.971 (0.956; 0.986)                 | 0.0002  |
| PEEP (cmH₂O)                                   | 0.944 (0.910; 0.979)                 | 0.0017  |
| Active/hematologic neoplasm or immunosuppression (ref. no.) | 1.414 (1.111; 1.801)             | 0.0050  |
| SOFA score – Cardiovascular                     | 0.925 (0.870; 0.984)                 | 0.0139  |
| Heart failure (ref. no.)                       | 1.482 (1.080; 2.033)                 | 0.0148  |
| Outcome—excess oxygen use at day 1 (model° on 1694 patients) |                                      |         |
| P/O/FIO₂ (mmHg)                                | 0.978 (0.976; 0.980)                 | < .0001 |
| PEEP (cmH₂O)                                   | 1.144 (1.091; 1.199)                 | < .0001 |
| PIP (cmH₂O)                                    | 1.029 (1.014; 1.045)                 | 0.0002  |
| Bicarbonate (mmol/L)                           | 0.971 (0.954; 0.989)                 | 0.0013  |
| Age (years)                                    | 0.988 (0.981; 0.996)                 | 0.0023  |
| BMI (kg/m²)                                    | 0.980 (0.965; 0.995)                 | 0.0111  |
| Tidal volume (ml/kg IBW)                       | 1.081 (1.017; 1.149)                 | 0.0122  |

Abbreviations: BMI body mass index, FIO₂ fraction of inspired oxygen, PEEP positive end-expiratory pressure, PIP peak inspiratory pressure, SOFA sepsis-related organ failure, P/O₂ arterial oxygen partial pressure, IBW ideal body weight

*Multivariable logistic model with presence of hyperoxemia (PaO₂ > 100 mmHg) as dependent dichotomous variable and the predictors were identified by stepwise approach. One hundred and fifty patients were excluded due to missing values for the response or explanatory variables. List of possible predictors in stepwise approach: age, sex, body mass index, comorbidities (presence of heart failure, diabetes mellitus chronic renal failure, chronic obstructive pulmonary disease or home ventilation, active neoplasm of hematologic neoplasm or immunosuppression), ARDS risk factors (none, only non-pulmonary, only pulmonary, both types), bicarbonates concentration, management factors (presence of invasive mechanical ventilation, tidal volume, PEEP, PIP, total respiratory rate, minute ventilation), and FIO₂ and SOFA components (CNS, cardiovascular, renal, liver, coagulation score)

°Multivariable logistic model with excess of oxygen use (FIO₂ ≥ 0.6 and PaO₂ > 100 mmHg) as dependent dichotomous variable and predictors identified by stepwise approach. Three hundred and eleven observations were deleted due to missing values for the response or explanatory variables

List of possible predictors in stepwise approach: age, sex, body mass index, comorbidities (presence of heart failure, diabetes mellitus chronic renal failure, chronic obstructive pulmonary disease or home ventilation, active neoplasm of hematologic neoplasm or immunosuppression), ARDS risk factors (none, only non-pulmonary, only pulmonary, both types), bicarbonates concentration, management factors (presence of invasive mechanical ventilation, tidal volume, PEEP, PIP, total respiratory rate, minute ventilation), and PaO₂/FIO₂ ratio and non-respiratory SOFA components (CNS, cardiovascular, renal, liver, coagulation score)
Oxygen use, and outcome in early ARDS, in this patient cohort.

Oxygen use in ARDS
The optimal use of oxygen in patients with ARDS remains unclear. While guidelines recommend the use of supplemental oxygen during acute hypoxemia [38], specific therapeutic goals in terms of PaO₂ or SpO₂ are lacking. The ARDS Network targeted a PaO₂ of 55–80 mmHg in the ARMA trial of patients with ARDS [39]. The British Thoracic Society suggested a target SpO₂ of 94–98% in acutely ill patients who are not at risk of hypercapnic respiratory failure (only Grade D recommendation) [40, 41].

Tissue hypoxia directly causes cellular death, leading to organ failure and increased mortality in ICU patients. In contrast, high oxygen concentrations may be directly toxic to the lung via mechanisms that remain poorly characterized but may include alveolar-capillary “leak” and fibrogenesis [42, 43], arterial vasoconstriction [18, 19], and the production of reactive oxygen species with consequent proinflammatory and cytotoxic effects [20–22]. Consequently, clinicians are faced with the task of titrating the amount of oxygen delivered to avoid both hypoxemia and hyperoxemia. Prior studies show that clinicians appear to use higher FIO₂ than is necessary in the critically ill [3]. While the reasons are unclear, potential explanations include concerns over the need to avoid tissue hypoxia, [4, 5] a desire to provide a “buffer” should a clinical deterioration occur, or because the consequences of hyperoxia are considered less severe than hypoxia.

Hyperoxemia in ARDS
In this study, hyperoxemia was seen on day 1 in a third of ARDS patients enrolled in the LUNG SAFE study. The fact that hyperoxemia was more prevalent than hypoxemia in patients immediately following the onset of ARDS, might seem surprising given that ARDS is a syndrome defined by impaired gas exchange but presumably reflects the effectiveness of ventilatory support and oxygen therapy. Of interest, hyperoxemia was associated with lower SOFA cardiovascular scores, suggesting that clinicians were not permitting hyperoxemia as a “buffer” in patients with shock. In this patient cohort, hyperoxemia was relatively transient in the majority of patients in early ARDS.
A minority of patients had sustained hyperoxemia in this cohort. Interestingly, day 2 median FIO\textsubscript{2} was the same in patients with sustained hyperoxemia and normoxemia, while P/F ratio was substantially higher in the hyperoxemic patients. These findings suggest that sustained hyperoxemia in these patients is a function of rapidly improving gas exchange rather than excess oxygen use. Sustained hyperoxemia did not have a demonstrable impact on patient mortality. In the matched propensity score analysis, outcomes in patients with sustained hyperoxemia were comparable to that seen in normoxemic patients.

These findings contrast with prior findings regarding hyperoxemia in other critically ill cohorts. However, an important difference between these studies and the current study relates to the severity of hyperoxemia. De Jonge and colleagues reported an association between early hyperoxemia and outcome in patients with acute respiratory failure in the Netherlands [44]. However, this association was only seen in patients with relatively severe hyperoxemia (PaO\textsubscript{2} > 123 mmHg; uncommon in our cohort) and only on day 1 of ICU admission, while there was no adverse association between hyperoxia over the entire ICU stay and patient outcome. The potential for harm from hyperoxia in the critically ill appears to be enhanced with greater severity and “dose” of hyperoxemia [45]. In fact, in critically ill patient groups where lung function was relatively preserved, such as patients post cardiac arrest, harm was mainly associated with systemic oxygen tensions over 300 mmHg [13]. Greater degrees of hyperoxemia were likely in both the study by Girardis et al. [24] and in the HYPERS2S trial [23] of “induced” systemic hyperoxemia in patients with sepsis. Our study was focused solely on patients with ARDS, where due to their impaired gas exchange, they cannot attain this severity of systemic hyperoxemia.

**Oxygen use in ARDS**

High inspired oxygen use was frequent in patients on day 1 of ARDS, with two thirds of patients with systemic hyperoxia receiving at least 60% oxygen in day 1—which we termed “excess oxygen use” on the basis that these patients could safely have had their FIO\textsubscript{2} reduced while maintaining normoxemia. Of importance, high FIO\textsubscript{2} use...
was frequently transient, with a marked decrease in higher inspired oxygen concentration use on day 2. Nevertheless, at each decile of FIO₂, approximately one third of patients were hyperoxemic, suggesting the potential existed to further reduce oxygen use. Of interest, there was an association between excess oxygen use and the use of higher tidal volumes.

Our unadjusted analyses suggested an association between higher FIO₂ and poorer outcome. However, in multivariate analyses, which accounted for lung injury severity, we found no independent association between high FIO₂ use and patient outcome. Propensity-matched analyses in patients excess FIO₂ confirmed no difference in mortality compared to normoxemic patients.

Our findings do not support prior concerns [24] raised regarding the use of higher FIO₂ in patients with ARDS that are not hypoxemic. This finding also contrasts with the analysis of patients in the ARDS Network trials that found that the cumulative duration of “above target” oxygen exposure (FIO₂ above 0.5 in ARDS patients while PaO₂ was > 80 mmHg) was associated with mortality [27]. While the reasons for the divergent findings are unclear, potential explanations include the fact that our analysis concentrated on early ARDS, the fact that high FIO₂ use was transient in most patients in our cohort, and the fact that this analysis may have been better adjusted for the impact of lung injury severity.

**Limitations**

This study has several limitations. The non-linearity of P/F ratio at different FIO₂ [46] makes it difficult to predict the effect of FIO₂ on PaO₂/FIO₂, especially when matching patients with mild ARDS. While we have adjusted our analyses to account for known measured confounders, the possibility remains that some of our findings may arise from unmeasured or residual confounding. Moreover, we cannot make causal inferences for any associations seen, given the observational nature of our study. Our dataset comprises daily arterial blood gas and FIO₂ data, taken at a standardized time each morning. It is possible that these data do not properly reflect the spectrum of FIO₂ use and PaO₂ data over the course of that day. Given this, in the hyperoxemia analyses, we focused on patients that were hyperoxemic on both days 1 and 2 of ARDS. There are no single accepted definitions for hyperoxemia, hypoxemia, or excess oxygen use, so our definitions are of necessity arbitrary, and other definitions have been used in other analyses. This could partly explain any divergence in findings across these studies. Lastly, our assumption that

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**Table 3** Factors associated with hospital mortality in study population (n = 2005) and in patients with hyperoxemia at day 1 (n = 607)

| Factor                                         | Odds ratio (95% confidence interval) | p value |
|------------------------------------------------|-------------------------------------|---------|
| **Study population (n = 2005)—model on 1360 patients** |                                     |         |
| Age (year)                                     | 1.022 (1.015; 1.030)                | <.0001  |
| BMI (kg/m²)                                    | 0.978 (0.962; 0.995)                | 0.0098  |
| SOFA score—cardiovascular                      | 1.182 (1.096; 1.275)                | <.0001  |
| SOFA score—respiratory                         | 1.405 (1.182; 1.669)                | 0.0001  |
| SOFA score—renal                               | 1.209 (1.087; 1.344)                | 0.0005  |
| SOFA score—central nervous system               | 1.147 (1.061; 1.240)                | 0.0006  |
| Active/hematologic neoplasm or immunosuppression (ref. no.) | 2.248 (1.697; 2.978)                | <.0001  |
| Chronic liver failure (ref. no.)                | 4.315 (2.184; 8.523)                | <.0001  |
| PIP (cmH₂O)                                    | 1.030 (1.013; 1.046)                | 0.0003  |
| Invasive mechanical ventilation (ref. no.)      | 0.497 (0.339; 0.729)                | 0.0044  |
| Bicarbonate (mmol/L)                           | 0.979 (0.960; 0.997)                | 0.0240  |
| **Patients with PaO2 > 100 mmHg (n = 607)—model on 530 patients** |                                     |         |
| Age (year)                                     | 1.031 (1.018; 1.044)                | <.0001  |
| SOFA score—renal                               | 1.362 (1.152; 1.610)                | 0.0003  |
| SOFA score—cardiovascular                      | 1.205 (1.073; 1.352)                | 0.0016  |
| Active/hematologic neoplasm or immunosuppression (ref. no) | 1.828 (1.186; 2.819)                | 0.0063  |
| Chronic liver failure (ref. no.)                | 4.091 (1.256; 13.328)               | 0.0194  |
| Total respiratory rate (breath/min)             | 1.043 (1.015; 1.072)                | 0.0027  |
| Bicarbonate (mmol/L)                           | 0.958 (0.924; 0.994)                | 0.0210  |

**Abbreviations:** BMI body mass index, PIP peak inspiratory pressure, SOFA sepsis-related organ failure assessment.
inpatients at day 90 survived to hospital discharge is a further limitation.

Conclusions
Our findings demonstrate that hyperoxemia and high fractional inspired oxygen use is prevalent in patients with early ARDS in patients enrolled in the LUNG SAFE cohort. Higher FIO2 use decreased from day 1 to day 2 of ARDS, with most day 2 hyperoxemia seen in patients at lower FIO2, in whom gas exchange was improving. Reassuringly, we found no relationship between hyperoxemia or excessive oxygen use and patient outcome in this cohort.

Supplementary information
Supplementary information accompanies this paper at https://doi.org/10.1186/s13054-020-2826-6.

Additional file 1. Online Methodology and eTables. Expanded Methods and Materials. eTable 1: Comorbidities and risk factors in study population (n = 2005), stratified by arterial oxygenation on day 1. eTable 2: Characteristics of patients with sustained normoxemia and sustained hyperoxemia. eTable 3: Characteristics at ARDS onset and clinical outcomes in matched sample (n = 354) of patients with sustained normoxemia and with sustained hyperoxemia. eTable 4: Characteristics at ARDS onset and clinical outcomes in matched sample (n = 646) of patients with normoxemia and with excess oxygen use at day 1.

Fig. 5 Kaplan-Meier curves for hospital survival in matched samples. a Survival probability in matched sample (n = 448) of patients with sustained normoxemia and with sustained hyperoxemia. b Survival probability in matched sample (n = 646) of patients with normoxemia and with excess oxygen use at day 1. Notes: (1) Normoxemia is defined as 55 mmHg ≤ PaO2 ≤ 100 mmHg on day 1 of ARDS, sustained normoxemia defined as normoxemia on day 1 and 2 of ARDS, sustained hyperoxemia defined as PaO2 > 100 mmHg on day 1 and 2 of ARDS, and excess oxygen use defined as PaO2 > 100 mmHg and FIO2 ≥ 0.60 on day 1 of ARDS. (2) Mortality is defined as mortality at hospital discharge or at 90 days, whichever event occurred first. We assumed that patients discharged alive from the hospital before 90 days were alive on day 90. (3) The number of patients at risk reported at the bottom of the figure is referred to as the end of the corresponding day.

Abbreviations
ARDS: Acute respiratory distress syndrome; ICUs: Intensive care units; LUNG SAFE: Large Observational Study to Understand the Global Impact of Severe Acute Respiratory Failure; ESICM: European Society of Intensive Care Medicine; PaO2: Arterial oxygen tension; FIO2: Fraction of inspired oxygen; MV: Invasive mechanical ventilation; ANOVA: Analysis of variance; LOESS: Locally estimated scatterplot smoothing; OR: Odds ratio; CI: Confidence interval; SOFA: Sepsis-related organ failure assessment

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Authors' contributions

JL, GB, and LB conceived of and designed this study, interpreted the data, drafted the manuscript, and revised the manuscript for important intellectual content. FM, TP, EF, and ER contributed to the acquisition of data, conducted data cleaning, analyzed the data, interpreted the data, and revised the manuscript for important intellectual content. All of the authors reviewed, discussed, and approved the final manuscript.

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The authors declare that they have no competing interests.

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