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ORIGINAL

ESICM—ESPNIC international expert consensus on quantitative lung ultrasound in intensive care

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Abstract

Purpose: To provide an international expert consensus on technical aspects and clinical applications of quantitative lung ultrasound in adult, paediatric and neonatal intensive care.

Methods: The European Society of Intensive Care (ESICM) and the European Society of Paediatric and Neonatal Intensive Care (ESPNIC) endorsed the project. We selected an international panel of 20 adult, paediatric and neonatal intensive care experts with clinical and research expertise in quantitative lung ultrasound, plus two non-voting methodologists. Fourteen clinical questions were proposed by the chairs to the panel, who voted for their priority (1–9 Likert-type scale) and proposed modifications/supplementing (two-round vote). All the questions achieved the predefined threshold (mean score > 5) and 14 groups of 3 mixed adult/paediatric experts were identified to develop the statements for each clinical question; predefined groups of experts in the fields of adult and paediatric/neonatal intensive care voted statements specific for these subgroups. An iterative approach was used to obtain the final consensus statements (two-round vote, 1–9 Likert-type scale); statements were classified as with agreement (range 7–9), uncertainty (4–6), disagreement (1–3) when the median score and ≥ 75% of votes laid within a specific range.

Results: A total of 46 statements were produced (4 adults-only, 4 paediatric/neonatal-only, 38 interdisciplinary); all obtained agreement. This result was also achieved by acknowledging in the statements the current limitations of quantitative lung ultrasound.

Conclusion: This consensus guides the use of quantitative lung ultrasound in adult, paediatric and neonatal intensive care and helps identify the fields where further research will be needed in the future.

Keywords: Quantitative lung ultrasound, Lung ultrasound score, Aeration, Lung monitoring, Critical care ultrasound, Neonates

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Introduction

Lung ultrasound (LUS) has seen an exponential diffusion in the last few years, particularly in critical care [1, 2]. It provides easy, repeatable and clinically useful information at the bedside, making it a typical point-of-care tool. Beyond the information mainly used for diagnostic purposes (i.e., "qualitative LUS") [3], the last few years saw an increasing use of LUS scores to provide quantitative assessments (i.e. "quantitative LUS") [4]. In critical care, this allows the evaluation of lung aeration, that would otherwise require invasive/irradiating techniques, eventually necessitating transportation, or would be unfeasible in the smallest patients, such as neonates and infants. Thus, the use of quantitative LUS has found an increasingly important space in critical care as a diagnostic and monitoring tool and represents one of the few cross-disciplinary examples of tools similarly used in adult (ICU), paediatric (PICU) and neonatal intensive care units (NICU). Nonetheless, several questions are still open, and there is a substantial inhomogeneity in the calculation and interpretation of LUS scores [5, 6]. Given the usefulness and the increasing diffusion of the technique, the European Society for Intensive Care Medicine (ESICM) and the European Society for Paediatric and Neonatal Intensive Care (ESPNIC) have created a joint project to analyse the available literature and issued an expert consensus of the use of quantitative LUS in adult, paediatric and neonatal intensive care.

Take-home message

Lung ultrasound can be applied in a quantitative manner in critically ill patients, mainly to quantify and monitor lung aeration at the bedside accurately. We provide consensus statements regarding technical aspects and clinical applications of quantitative lung ultrasound in adult, paediatric and neonatal critically ill patients.

Methods

We followed the ACCORD (ACcurate COnsensus Reporting Document) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines for this project, including the manuscript draft phase (electronic supplementary material 1) [7, 8]. An agreement between ESICM and ESPNIC was reached and the research protocol was approved by the two societies, as per their internal procedures; the protocol was not prospectively registered. We have chosen a Delphi consensus instead of clinical practice guidelines as format since a low quality of evidence was expected; accordingly, no grading of evidence is provided. Addendum to methods can be found in electronic supplementary material 1.

Panel composition

The Steering Committee for the project was composed of two co-chairs (SM, DDL, representative of ESICM and ESPNIC, respectively) and two methodologists (AC, MRG) appointed following the approval of the two societies. The Committee determined the methodology, drafted the protocol, established the criteria for experts' selection, identified the clinical questions and managed the voting process. Experts were required to have both established clinical expertise and research activity in quantitative LUS applied to critically ill patients. The clinical experience was defined as more than 10 years of work in adult or paediatric/neonatal intensive care; paediatric and neonatal practice were considered as a unique category. The ratio between adult and paediatric experts was not decided a priori. The research activity criterion was fulfilled if at least 4 original works (of which at least 2 as last/first author) on quantitative LUS were published in the last 10 years. Research and clinical competencies were considered as overriding criteria; however, the panel aimed to have a fair gender balance, to include at least one ESICM NEXT researcher (≤35-year-old) and clinicians with clinical/research experience in low/middle-income countries (LMIC). The two chairs invited the selected panellists by email on October 30th, 2023; all accepted the first invitation. The invited panellists were neither requested nor allowed to suggest other panel members. No fees or incentives were proposed for participation. Finally, the expert panel included 20 clinicians (comprised of intensivists and one physiotherapist) from 8 countries, 1 ESICM NEXT member (MS), 35% of women and 3 experts in LMIC setting (LP, IC, MS). No patient or caregiver representatives were invited due to the highly technological and specific nature of the work.

Clinical questions

The followed workflow is displayed in electronic supplementary material 1. An initial list of 14 clinical questions was drafted by the chairs and anonymously voted for priority by the panel using a 1–9 Likert-type scale with an online Google module (1st round of vote); an open text section was also available for each question to comment as well as an extra question for suggestions; two weeks were given to vote (questionnaire and results are reported in electronic supplementary material 2). Based on the model developed by UCLA-RAND Corporation [9], results classified the questions into low priority (1–3 mean score = dismissed), intermediate priority (4–6 = modified to be revoted or reconsidered) and high priority ("critical") (7–9 = preserved). In the 2nd round of votes, the panellists anonymously voted the questions added/modified according to their suggestions;

all questions with a mean score > 5 were included (as reported in ESM3). During an online meeting on March 14th, 2024, the clinical questions were discussed and mixed adult/paediatric-neonatal subgroups of at least three experts were appointed for each question to elaborate the statements and rationales with the only exception of question n.11. Given the nature of its topic, this latter was treated by two paediatric/neonatal experts only. The steering committee discussed the statements with each group and, when necessary, helped refining them.

We then investigated the consensus reached on each statement and rationale which were divided into three groups according to their nature: 1) general (i.e., dedicated to aspects of quantitative LUS involving all the experts), 2) "adult" (i.e., dedicated to topics concerning adult patients only), 3) "paediatric/neonatal" (i.e., dedicated to topics concerning children and neonates only). General statements/rationales were voted on by all panellists, while adult and paediatric/neonatal ones were voted on only by panel members with the corresponding clinical expertise, according to predefined groups' definition as proposed by the steering committee and approved by the panel (electronic supplementary material 4). Opinions were expressed using the aforementioned Likert-type scale [9]; a space for free comments was left; three weeks were given to vote (October 1st-24th, 2024). The Likert-type scale was split into three sections: a score of 1–3 implicated rejection or disagreement ("not appropriate"); 4–6 implicated ("uncertainty"); and 7–9 implicated agreement/support ("appropriate"), as done for previous consensus projects in adult and paediatric intensive care. [10, 11] Consensus was reached when (i) 75% or more of the respondents (excluding the methodologists) assigned a score within the 1–3 or 7–9 ranges, which rejected or accepted the statements/rationales, respectively; and (ii) the median score also laid within these ranges [12]. The type of consensus achieved was determined by the median score: "agreement" was defined for a median score ≥ 7, and "disagreement" for a median score ≤ 3. A median score within the 4–6 range meant that most of the group had scored the items as "uncertain."[12] Questionnaires and results of the first round of statements' vote are displayed in electronic supplementary material 5. Two statements with uncertainty and a single statement with agreement were modified according to experts' comments and revoted at the second round on November 1st-22nd (questionnaires and results in electronic supplementary material 6). All panellists always participated in every work step (i.e. response rate always 100%).

The authors underline that the statements were based on experts' clinical and research experience, were issued from the discussion among the panellists and represent this group of experts' recommendations; no grading of certainty of evidence could be provided, as requested for formal guidelines.

Results

A total of 46 statements were produced: 38 for the entire panel, 4 adults only and 4 paediatric/neonatal only. A summary of all statements and their median scores is displayed in Table 1.

Question 1: In ICU-admitted patients, how should we name the LUS score?

STATEMENT 1.1: The term "lung ultrasound" should be preferred to "thoracic ultrasound" in defining the score.

RATIONALE: While most studies focused imaging the lung parenchyma with ultrasound use the term "lung ultrasound", "thoracic ultrasound" has also been used even when specifically referring to lung imaging [13–16]. A smaller number of studies used "thoracic ultrasound" to refer to multi-organ thoracic imaging (e.g., lung and diaphragm) [17]. To improve clarity, when ultrasound imaging is limited to the lung, the term "lung ultrasound" (i.e., the acronym LUS) should be used instead of thoracic ultrasound.

STATEMENT 1.2: The calculation of a LUS score is a quantitative approach. "Quantitative lung ultrasound" (quantitative LUS) is a general term indicating multiple different visual/automated approaches using lung ultrasound in a quantitative manner.

RATIONALE: LUS scores were frequently considered semiquantitative, but what constitutes a semiquantitative score is only well-defined in laboratory medicine (i.e., estimation of the approximate concentration of a given substance as opposed to its precise measure) and less accepted beyond this specialty. As opposed to qualitative lung ultrasound, quantitative LUS includes the use of scores to systematically measure the loss of pulmonary aeration. While validation studies have not focused on the calibration of these scores, some have shown interval scale-like properties, allowing comparison to other quantitative assessments of lung aeration as quantitative CT scan [18–20]. LUS scores can, therefore, be considered as a numeric discrete variable, and, therefore, a quantitative approach. The authors suggest to use the term "quantitative LUS" to indicate, in general, the use of the technique in a quantitative manner, including also automation, for different purposes [4].

STATEMENT 1.3: The term "lung ultrasound aeration score" (abbreviated "LUS Aeration Score") should be used when referring to the scoring system applied to quantify lung aeration.

Table 1 Final statements and relative scores and percentage of agreement

Question 1: in icu-admitted patients, how should we name the LUS score?	
STATEMENT 1.1: The term "lung ultrasound" should be preferred to "thoracic ultrasound" in defining the score	9.0 [9.0–9.0] 8.7 ± 0.7 100%
STATEMENT 1.2: LUS score is a quantitative approach. "Quantitative lung ultrasound" (quantitative LUS) is a general term indicating multiple different visual/automated approaches using lung ultrasound in a quantitative manner	9.0 [8.0–9.0] 8.4 ± 1.2 85.0%
STATEMENT 1.3: The term "lung ultrasound aeration score" (abbreviated "LUS Aeration Score") should be used when referring to the scoring system applied to quantify lung aeration	9.0 [8.0–9.0] 8.4 ± 1.0 95.0%
Question 2: In ICU-admitted patients, how many regions should be examined to compute the score and how should they be identified?	
STATEMENT 2.1: In ICU-admitted adults, adolescents and in children aged more than one year, the LUS aeration score should be computed in six regions per hemithorax; anterior, lateral, and posterior fields are identified by sternum, anterior, and posterior axillary lines; each field is divided into superior and inferior regions	9.0 [8.0–9.0] 8.4 ± 1.4 90.0%
STATEMENT 2.2 PEDNEO: In neonates and infants below one year of age the score can be computed in two ways: A) simplified, to be used in the first 24-48 h of life (one lateral and two anterior regions with no posterior regions, i.e., three regions per hemithorax); B) extended, to be used after the first 24-48 h (as in adults but with one single lateral region, i.e., five regions per hemithorax)	9.0 [9.0–9.0] 7.7 ± 2.7 77.8%
STATEMENT 2.3: Some applications of LUS aeration score can be performed with a simplified approach (i.e., in a limited number of regions) in patients of any age	9.0 [8.0–9.0] 8.2 ± 1.8 90.0%
STATEMENT 2.4: Any effort should be done to obtain a complete examination; in adult patients where this is unfeasible, a score indexed on the accessible number of regions has been proposed; however, in non homogeneous diseases and when multiple regions are missing, this approach can be at risk of misleading conclusions	8.5 [8.0–9.0] 8.4 ± 0.7 100%
STATEMENT 2.5: The regions are named according to their location with an acronym including side, field, upper/lower (e.g. Left Upper Anterior – LUA) or side and a numerical order (Right R1-6, Left L1-6)	9.0 [8.0–9.0] 8.6 ± 0.6 100%
Question 3. In ICU-admitted patients, which machine setting should be preferred?	
STATEMENT 3.1: In adults, a standard examination should start with a linear probe in anterior fields and switch to a low-frequency probe in posterior fields. In children, neonates and infants, a high-frequency linear probe should be preferred	8.0 [7.0–9.0] 7.5 ± 1.9 80.0%
STATEMENT 3.2: A transversal approach, aligned with the intercostal space, has advantages once the pleura is correctly identified in a longitudinal scan. No clear preferences on marker's position are available	9.0 [8.0–9.0] 8.4 ± 1.1 95.0%
STATEMENT 3.3: The following settings are advised: 1) turning off tissue harmonics, 2) turning off postprocessing/artifact removal/auto-optimization features, 3) field-depth at least twice the pleural depth. Building a customized "lung pre-set" may be helpful	8.0 [7.8–9.0] 8.0 ± 1.5 90%
STATEMENT 3.4: Hand-held devices are probably reliable for the quantification of lung loss of aeration in adults. Their use in ICU-admitted children and neonates is possible but not validated	8.0 [7.8–9.0] 8.2 ± 0.8 100%
Question 4: in ICU-admitted patients, how should the progressive steps of loss of aeration be defined and the score computed?	
STATEMENT 4.1: The progressive loss of lung aeration in critical patients of any age should be defined in four steps (0–1-2–3, from the most to the least aerated); this approach has been validated with quantitative CT and extravascular lung water (EVLW) in adults, and with EVLW, oxygenation, lung mechanics and biological assays in neonates	9.0 [8.8–9.0] 8.7 ± 0.7 100%
STATEMENT 4.2: To distinguish between score 1 and 2 (i.e., mild vs. Moderate loss of aeration) of the 0–3 scale, two approaches have been proposed: coalescence-based and quantitative-based. In adults, the quantitative-based approach outperforms the coalescence-based in terms of assessment of aeration, correlation with CT/EVLW and interobserver agreement	9.0 [8.0–9.0] 8.6 ± 0.8 95%
STATEMENT 4.3: The score 3 (severe loss of aeration) is attributed when a large consolidation is detected. To this aim, consolidations can be quantified by measuring the distance from the pleural line to its deepest edge (> 2–2.5 cm in adults; > 1 cm or > 0.5 cm/kg in neonates)	9.0 [8.0–9.0] 8.4 ± 0.9 95.0%
Question 5: In ICU-admitted patients, is the automated/assisted score calculation reliable and useful?	
STATEMENT 5.1: Automated/assisted quantitative lung ultrasound has the potential to reduce inter- and intra-observer variability and create a unique quantification system	8.0 [7.0–8.3] 7.6 ± 1.2 80.0%
Question 6: for ICU clinicians, which is the minimum required training to correctly compute the LUS aeration score?	
STATEMENT 6.1: Theoretical-practical training in LUS varies widely but enhances participants' knowledge regardless ofpatients' age	9.0 [8.0–9.0] 8.3 ± 1.6 95.0%
STATEMENT 6.2: In adults, the minimum practical training required to accurately compute the LUS aeration score is 25 supervised examinations. In pediatrics, less precise data are available; from 2 weeks to 3 months of supervised practice seems to be a reasonable training timeframe	8.5 [7.8–9.0] 8.2 ± 1.0 90.0%

Table 1 (continued)

STATEMENT 6.3: The interobserver agreement between experts in LUS aeration score computation is near perfect irrespective of patients' age	8.0 [7.8–9.0] 7.8 ± 1.7 85.0%
Question 7: in patients admitted to ICU for respiratory failure, is LUS aeration score reliable, safe and suitable to assess and monitor lung aeration and the severity of the disease compared to other imaging (e.g., CT, CXR, electrical impedance tomography – EIT) and non-imaging (e.g., EVLW assessment) techniques?	
STATEMENT 7.1: Quantitative LUS can reliably assess and monitor lung aeration and severity of the disease in critically ill adults, children and neonates	9.0 [8.0–9.0] 8.5 ± 0.9 95.0%
STATEMENT 7.2: Evidence about quantitative LUS safety in terms of nosocomial infections and side-effects is limited	9.0 [7.8–9.0] 8.3 ± 1.0 95.0%
STATEMENT 7.3: Quantitative LUS is suitable and little time-consuming to assess and monitor lung aeration in adults, children and neonates	9.0 [8.0–9.0] 8.4 ± 1.1 95.0%
Question 8: in patients admitted to ICU for respiratory failure, is a quantitative approach reliable and suitable to define ARDS and its phenotype (focal/non-focal)?	
STATEMENT 8.1: LUS associated to clinical parameters is reliable and suitable to define ARDS in adults, children and neonates, when both LUS aeration score and pleural abnormalities are considered	9.0 [8.0–9.0] 8.6 ± 0.6 100%
STATEMENT 8.2—ADULTS: Quantitative LUS may be reliable and suitable to ARDS phenotyping and classify lung morphology in adult patients	9.0 [8.8–9.0] 8.7 ± 0.7 100%
Question 9: in patients admitted to ICU for respiratory failure, is LUS aeration score reliable and suitable to indicate and interpret specific diagnostic and/or therapeutic procedures?	
STATEMENT 9.1—PEDNEO: LUS aeration score is reliable and suitable to indicate surfactant replacement in neonates with RDS, ensuring its timely administration, and to monitor its effectiveness	9.0 [9.0–9.0] 8.3 ± 1.1 88.9%
STATEMENT 9.2: Quantitative LUS is reliable and suitable to assess EVLW and guide fluid therapies in adults, children and neonates	8.0 [7.0–9.0] 7.6 ± 1.4 80.0%
STATEMENT 9.3: There is no evidence supporting quantitative LUS to indicate and monitor bronchodilators	9.0 [8.8–9.0] 8.7 ± 0.6 100%
STATEMENT 9.4: In adults and children beyond the neonatal age, LUS aeration score may be reliable and suitable tool to prescribe, monitor and tailor respiratory physiotherapy	8.0 [7.0–9.0] 7.6 ± 1.4 80.0%
STATEMENT 9.5: LUS aeration score is reliable and suitable to assess PEEP-induced recruitment in adults; limited evidence is available in children and neonates	9.0 [7.8–9.0] 8.4 ± 1.0 95.0%
STATEMENT 9.6: LUS aeration score is reliable and suitable to monitor the effects of prone positioning, in patients of any age	9.0 [8.0–9.0] 8.4 ± 10 90.0%
STATEMENT 9.7: To date, there is no evidence to support quantitative LUS for assessment and monitoring of lung hyperinflation; a reduced sliding in the anterior fields may suggest hyperinflation, but limited data are available	9.0 [8.0–9.0] 8.4 ± 1.1 95.0%
Question 10: in patients admitted to ICU for respiratory failure, is quantitative LUS reliable and suitable to predict weaning failure and other clinical outcomes?	
STATEMENT 10.1: LUS aeration score combined with clinical parameters is reliable and suitable to predict weaning and extubation failure in adults, children and neonates	8.5 [8.0–9.0] 8.3 ± 1.0 90.0%
STATEMENT 10.2—PEDNEO: LUS aeration score is reliable and suitable for early prediction of BPD in preterm infants	9.0 [8.0–9.0] 8.3 ± 1.1 88.9%
STATEMENT 10.3: LUS aeration score seems reliable and suitable to predict the need, monitor the efficacy and predict the failure of non-invasive respiratory supports in children and neonates; scarce data are available in adults	8.5 [8.0–9.0] 8.1 ± 1.2 85.0%
STATEMENT 10.4—ADULTS: LUS aeration score may be associated with ICU mortality in adult COVID-19 patients and probably in non-COVID-19 acute respiratory failure; inconclusive data are available for length of mechanical ventilation, ICU and hospital stay	8.0 [7.0–9.0] 7.7 ± 1.5 83.3%

Table 1 (continued)

STATEMENT 10.5: Quantitative LUS is reliable and suitable to predict post-operative complications in adults and children	9.0 [8.0–9.0] 8.1 ± 1.3 85.0%
Question 11—PEDNEO: in NICU-admitted patients is lus aeration score reliable and suitable to diagnose lung/thoracic malformations or to confirm the prenatal diagnosis of lung/thoracic malformations?	
STATEMENT 11.1: Qualitative LUS is suitable to diagnose/confirm the diagnosis of malformations, but its reliability is unknown as well as the role of quantitative LUS	9.0[8.0–9.0] 8.3 ± 1.1 88.9%
Question 12: in patients under mechanical ventilation, is quantitative LUS reliable and suitable to suspect and monitor ventilator-associated pneumonia (VAP)?	
STATEMENT 12.1—ADULTS: In mechanically ventilated adults, an increase in LUS aeration score corresponding to a worsening of lung aeration is reliable and suitable to rise VAP suspicion when clinical criteria are met	8.0 [7.0–9.0] 7.9 ± 1.1 91.7%
STATEMENT 12.2: Scoring systems including clinical, microbiological parameters and specific LUS patterns are reliable and suitable to rule in/out VAP in adults; the dynamic linear-arborescent air bronchogram is the sign with the highest specificity. Similar clinical-ultrasound scores have been reported in pediatrics and neonates; however, scarce data preclude firm statements about their generalized use	9.0 [8.8–9.0] 8.5 ± 1.1 90.0%
STATEMENT 12.3: Serial LUS aeration scores are suitable and reliable in early detection of antibiotic-induced lung reaeration or extension of lung infection in case of antimicrobial success/failure in adults with VAP. Thus, LUS aeration score may help in evaluating the duration of antibiotic therapy. This might also be possible in neonates, but scanty data are available	9.0 [8.0–9.0] 7.9 ± 1.9 85.0%
Question 13: in hospitalized patients at risk of respiratory failure, is LUS aeration score reliable and suitable for an early detection and monitoring of respiratory deterioration?	
STATEMENT 13.1: Quantitative LUS is reliable and suitable for early detection and monitoring of respiratory deterioration and/or ARDS development in hospitalized adults, children and neonates with several conditions including respiratory disorders and renal failure	9.0 [8.0–9.0] 8.4 ± 1.1 90.0%
Question 14: is quantitative LUS reliable and suitable in specific clinical conditions?	
STATEMENT 14.1: QUANTITATIVE LUS AND **COVID-19**: In association with physical examination and clinical criteria, LUS aeration score is reliable and suitable for COVID-19 triage and severity assessment in adult patients. In pediatric and neonatal patients with COVID-19, quantitative LUS is similarly suitable but its reliability for triage and severity assessment is uncertain	9.0 [8.0–9.0] 8.6 ± 0.8 95.0%
STATEMENT 14.2 ADULTS: QUANTITATIVE LUS AND **PREGNANT PATIENTS**: Quantitative LUS is reliable and suitable in pregnant patients, allowing the detection of cardiogenic pulmonary oedema, pre-eclampsia-related pulmonary oedema, SARS-CoV-2 pneumonia and others pulmonary complications	8.5 [8.0–9.0] 8.2 ± 1.2 91.7%
STATEMENT 14.3: QUANTITATIVE LUS AND **CARDIOGENIC PULMONARY EDEMA (CPE)**: Quantitative LUS is reliable and suitable to detect CPE and indicate ICU admission in adult patients and probably in pediatric too	8.0 [8.0–9.0] 8.3 ± 0.9 95.0%
STATEMENT 14.4: QUANTITATIVE LUS AND **ECMO**: LUS aeration score is suitable to monitor lung aeration changes in adult, pediatric and neonatal ARDS patients receiving ECMO; there are insufficient data for its reliability and prognostic value	9.0 [7.8–9.0] 8.2 ± 1.3 90.0%
STATEMENT 14.5: QUANTITATIVE LUS IN **LMIC**: LUS aeration score is suitable in LMIC in critically ill adults, children and neonates but most of the available data are limited to non-ventilated patients	8.5 [8.0–9.0] 8.5 ± 0.5 100%

Data are reported as median score [IQR], mean ± standard deviation, percentage of agreement

ICU Intensive Care Unit, *LUS* Lung UltraSound, *PEDNEO* pediatric-neonatal, *CT* Computed Tomography, *EVLW* ExtraVascular Lung Water, *CXR_* Chest X-Ray, *ARDS* Acute Respiratory Distress Syndrome, *PEEP* Positive End-Expiratory Pressure, *BPD* Broncho Pulmonary Displasia, *COVID-19* Coronavirus Disease 2019, *VAP* Ventilator-Associated Pneumonia, *SARS-CoV-2* Severe Acute Respiratory, Syndrome Coronavirus 2, *CPE* Cardiogenic Pulmonary Edema, *ECMO* Extra-Corporeal Membrane Oxygenation, *LMIC* Low-Middle Income Country

RATIONALE: "Lung ultrasound score" is the most used term so far. Unfortunately, it may have different meanings and refers to a plethora of different approaches [21]. Various other names, e.g. "quantitative lung ultrasound score" [22] "lung ultrasound extension score"[23] "global lung ultrasound score" [24], "lung ultrasound aeration score"[20, 25] "lung ultrasound reaeration score"[26] have been proposed adding a word to further qualify the methodology ("global", "extension") or the purpose ("aeration", "reaeration"). "Quantitative lung ultrasonography" has also been used in a study investigating the diagnostic accuracy of Gray-scale analysis on LUS images [27]. Ideally, proper nomenclature should be self-explanatory. Therefore, "lung ultrasound aeration score" should be used to indicate the technique: this term reflects the purpose of the score which is to measure lung aeration. While multiple acronyms have been developed (e.g. LUSS, cLUSS, qLUSS, qLUS, nLUSS, %LUSS) [28, 29], none of them matches this name and the shorthand "LUS aeration score" is recommended by the authors and will be used from now on in the manuscript.

Question 2: in ICU-admitted patients, how many regions should be examined to compute the score and how should they be identified?

STATEMENT 2.1: In ICU-admitted adults, adolescents and in children aged more than one year, the LUS aeration score should be computed in six regions per hemithorax; anterior, lateral, and posterior fields are identified by sternum, anterior, and posterior axillary lines; each field is divided into superior and inferior regions.

RATIONALE: In adults and children beyond one year, a complete and systematic evaluation for the assessment of pulmonary aeration in ICU patients should include 12 regions (Fig. 1) [1]. The LUS aeration score is in fact normally computed in six regions per hemithorax: anterior, lateral, and posterior fields are identified by sternum, anterior, and posterior axillary lines; each field is divided into superior and inferior regions [1, 30]. With a 12-region approach, the global LUS aeration score correlated with overall lung loss of aeration when measured with quantitative CT [6, 19, 22]. This approach was used for the initial patient evaluation [1], to monitor pronation and positive end-expiratory pressure (PEEP) titration,[19, 26, 31], to guide antibiotic therapy [18], and physiotherapy [1, 32].

STATEMENT 2.2: In neonates and infants below one year of age the score can be computed in two ways: A) simplified, to be used in the first 24-48 h of life (one lateral and two anterior regions with no posterior regions, i.e., three regions per hemithorax); B) extended, to be used after the first 24-48 h (as in adults but with one single lateral region, i.e., five regions per hemithorax).

RATIONALE: In neonates, the regions' identification is similar but the thorax is much smaller and the described approaches are the only ones formally validated in this population (Fig. 1) [33, 34]. The simplified score does not consider the posterior regions in the first 24-48 h of life because: 1) the effect of gravity is less established and becomes clinically relevant only after a certain amount of time; 2) a relevant proportion of respiratory failures is represented by respiratory distress syndrome (RDS) caused by primary surfactant deficiency (particularly in preterm neonates) which is pathobiologically and ultrasonographically homogeneous [35, 36]. The 24-48 h time window describes uncertainties about the time needed

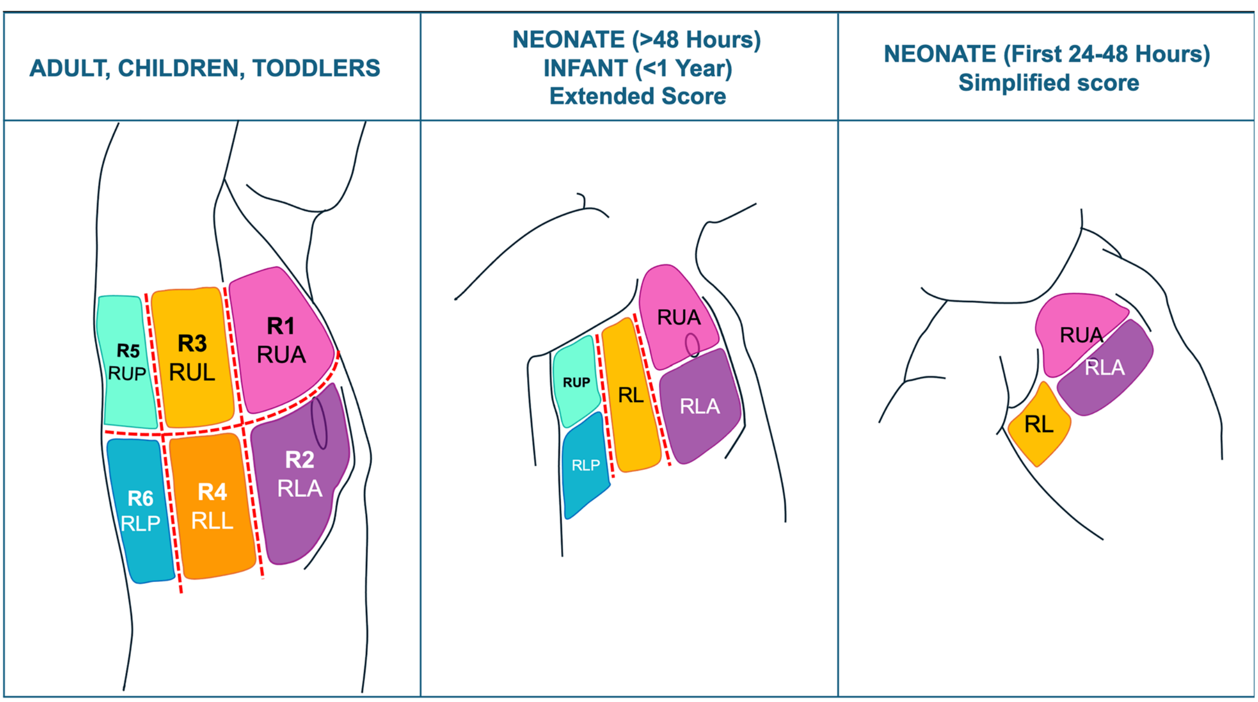

Fig. 1 Identification of the regions on the thorax for the computation of the lung ultrasound aeration score according to the age of the patient. A 12-region approach (6 per hemithorax) is recommended in adults and children > 1 year-old: anterior, lateral, and posterior fields are identified by sternum, anterior, and posterior axillary lines; each field is divided into superior and inferior regions (score ranging 0–36). In infants ≤ 1 year-old and neonates after the first 24–48 h of life, a 5-region per hemithorax approach with a single lateral region is recommended (score ranging 0–30; i.e. extended score). In neonates (particularly if preterm) for the first 24–48 h, a simplified approach limited to antero-lateral fields is advised (score ranging 0–18; i.e. simplified score)

to have the gravity effect and the proportion of respiratory failure due to disorders other than RDS. Therefore, with the current knowledge, it is advisable to use the simplified score until 24-48 h or for homogeneous lung injuries, while the extended score (i.e. including the posterior fields, as in older patients) should be used after 24-48 h of life or for heterogeneous lung injuries. In both approaches the lateral field is interrogated as a whole, due to the limited extension of the neonatal lateral surface [33].

STATEMENT 2.3: Some applications of LUS aeration score can be performed with a simplified approach (i.e., in a limited number of regions) in patients of any age.

RATIONALE: In adults, a simplified approach focused on anterior fields has been successfully used to phenotype acute respiratory distress syndrome (ARDS) and distinguish focal/non-focal diseases [37]. The evaluation of patients to be weaned from mechanical ventilation was reliable when the score was computed in anterior or anterolateral fields only [38, 39]. A 6-region approach (one anterior, one lateral, one posterior) showed strong correlation with a 12-region examination in SARS-CoV-2 disease (COVID-19) [40]. In neonates, the simplified score (Fig. 1) has been validated [34, 41–45], and is used to guide surfactant replacement [46, 47]. The simplified and extended approaches provide comparable accuracy to guide surfactant replacement on the first day of life and to predict bronchopulmonary dysplasia (BPD) after the first week of life [48–51]. The use of the extended score is, however, advised to evaluate lung aeration more comprehensively and monitor heterogeneous lung injuries, titrate respiratory support or guide pronation, particularly after 24-48 h of postnatal age [51–53].

STATEMENT 2.4: Any effort should be done to obtain a complete examination; in adult patients where this is unfeasible, a score indexed on the accessible number of regions has been proposed; however, in non-homogeneous diseases and when multiple regions are missing, this approach can be at risk of misleading conclusions.

RATIONALE: Some of the standard 12 lung regions may not be accessible to ultrasound because of dressings, open wounds, pneumothorax, pneumomediastinum, airleak, subcutaneous emphysema, or any condition limiting patient's mobilization. To overcome this issue, when less than 12 regions were accessible, some authors expressed the LUS aeration score as an 'involvement index' computed as the actual score/total score achievable $\times$ 100 [54]. In adults, this approach showed a significant correlation with computed tomography (CT), with a trend to underestimate the severity index [54]. Other authors circumvented this difficulty by attributing to the missing region the mean values of adjacent ones [55, 56]: this is practical and logical in homogeneous diseases (e.g. pulmonary oedema, RDS), but may be intrinsically wrong in inhomogeneous disorders (e.g., ARDS in patients of any age, BPD), or if multiple fields are missing. Henceforth, the LUS aeration score computation cannot be recommended as a general practice in patients in whom not all fields can be assessed.

STATEMENT 2.5: The regions are named according to their location with an acronym including side, field, upper/lower (e.g. Left Upper Anterior – LUA) or side and a numerical order (Right R1-6, Left L1-6).

RATIONALE: Each region is named according to its location as follows: right or left (R/L); upper or lower (U/L); anterior, lateral or posterior (A/L/P, e.g. right-upper anterior RUA – Fig. 1). In adults, a simplified nomenclature including the side (R/L) and the number of the region (1 = anterior-upper, 2 = anterior-lower, 3 = lateral-upper, 4 = lateral-lower, 5 = posterior-upper, 6 = posterior-lower) is also used [1].

Question 3. In ICU-admitted patients, which machine setting should be preferred?

STATEMENT 3.1: In adults, a standard examination should start with a linear probe in anterior fields and switch to a low-frequency probe in posterior fields. In children, neonates and infants, a high-frequency linear probe should be preferred.

RATIONALE: The probe's choice may have an impact on B-lines visualization [57]; in a study comparing probes on the visualization of B-lines, it seemed that convex and linear probes provided a good agreement between examiners and were superior to phased array probe [28, 57]. This may impact the computation of the LUS aeration score, and it is, therefore, of paramount importance to standardize the technique. High-frequency linear probes have better superficial definition (e.g. more defined pleural line, motion and artifacts), while low-frequency cardiac/convex probes provide better visualization of deeper findings (e.g. consolidations and effusions) and are more useful for the assessment of the lung bases.[1, 4]. Thus, for a complete examination and score computation in adults, this panel suggests that the standard approach should start with a linear probe in anterolateral fields and switch to a low-frequency probe in posterior ones or whenever a tissue-like pattern is visualized [6, 19, 20].

No strict recommendations for the choice of probe can be given for ICU-admitted children, given their variable size and weight. The transducers' frequency and footprint depend on age, chest wall depth and targeted structure. However, as a general rule, since paediatric patients need higher resolution and lower penetration of ultrasound beams, high-frequency (≈10–14 MHz) broadband linear transducers are valuable for scanning children and infants [30, 58, 59], while microlinear probes with smaller foot-print and higher frequency are preferred in neonates (≈14–20 MHz) particularly in premature ones [4]. Curvilinear/sectorial probes might be considered for neonates if no other probes are available but their use provides a relevant variability in beginners with less than 1 year of experience [60]. Ultra high-frequency (> 20 MHz) microlinear probes are available for neonates and have a greater axial resolution: their use can influence the score calculation by detecting more B-lines [61].

STATEMENT 3.2: A transversal approach, aligned with the intercostal space, has advantages once the pleura is correctly identified in a longitudinal scan. No clear preferences on marker's position are available.

RATIONALE: The probe can be oriented longitudinal (i.e., ribs and pleural line form the so-called "bat sign") or transversal (i.e., the probe is positioned between two ribs, perfectly aligned with them, avoiding ribs' shadow, Fig. 2). Since LUS artifacts are generated from the pleural line, a better alignment of the pleural line allows for a better artifacts' visualization. Accordingly, the transversal scan visualizes wider portions of pleura and more artifacts, facilitating the score computation in patients of any age [28, 62, 63]. For beginners, this panel considers advisable to start in a longitudinal scan to correctly identify the pleural line and then turn into the transversal scan. No clear indications are available on the marker's orientation, which is irrelevant to the score computation. The same approach used for qualitative ultrasound can be applied to quantitative one.

STATEMENT 3.3: The following settings are advised: 1) turning off tissue harmonics, 2) turning off postprocessing/artifact removal/auto-optimization features, 3) field-depth at least twice the pleural depth. Building a customized "lung pre-set" may be helpful.

RATIONALE: Few studies describe the exact machine settings used for LUS aeration score computation. Turning off tissue harmonics [24, 25, 64] and any postprocessing/artifact removal/auto-optimization features improve artifacts visualization [20, 25, 64]. Various depths depending on the probe can be found (linear 6–8 cm [24, 54]; convex 10–20 cm [65, 66]). A field depth set at least twice the pleural depth is considered reasonable by the authors to visualize A-lines. This shall, however, be adapted in paediatrics due to the variability of patient size; its impact on LUS aeration score computation is unknown. The position of the focal zone on the pleural line, the image gain setting, and the time-gain compensation were rarely described [20, 24, 64, 67]. Some experts use a "lung pre-set" which can be customized and helps standardizing lung imaging [67, 68].

STATEMENT 3.4: Hand-held devices are probably reliable for the quantification of aeration loss in

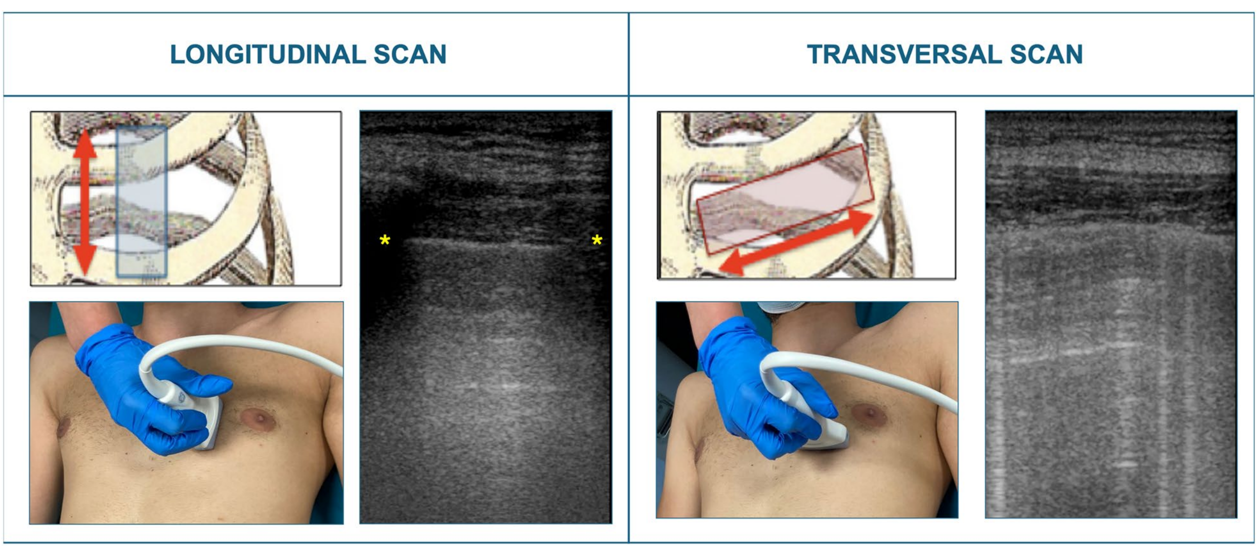

Fig. 2 Different approaches for lung scanning. In the longitudinal scan the probe is aligned to patient's cranio-caudal axis; this approach allows clear identification of the pleural line in the intercostal space by the visualization of the bat sign; however, the width of visualized pleura is limited by the ribs' shadow (*). In the transversal scan, the probe is perfectly aligned with the intercostal space: a wider pleura is explored, improving the performance of lung ultrasound in the computation of the lung ultrasound aeration score. Ribs are more horizontal in neonates and infants and the probe orientation shall be adjusted accordingly. The transversal scan has advantages in adults, children and neonates, once the pleural line is correctly identified

adults. Their use in ICU-admitted children and neonates is possible but not validated.

RATIONALE: Three studies compared LUS aeration scores computed with hand-held devices to CT severity scores, showing good correlation and excellent inter-rater agreement but also high imprecision; this may be due to limited possibilities of setting customization [54, 66, 69]. Although they are attractive, hand-held devices have not been vigorously investigated in children and may be less suitable in smaller patients; they, however, proved useful in identifying cardio-pulmonary diseases in rural Africa [70].

Question 4: In ICU-admitted patients, how should the progressive steps of loss of aeration be defined and the score computed?

STATEMENT 4.1: The progressive loss of lung aeration in critical patients of any age should be defined in four steps (0–1-2–3, from the most to the least aerated); this approach has been validated with quantitative CT and extravascular lung water (EVLW) in adults, and with EVLW, oxygenation, lung mechanics and biological assays in neonates.

RATIONALE: Several scores have been described to assess the loss of lung aeration. Many have only been compared to clinical variables and were not compared with other quantitative measures of aeration: thus, authors do not recommend their use in clinical practice. The best performing LUS aeration score is based on the identification of four steps of progressive loss of aeration, as follows: score 0 = normal aeration, score 1 = mild loss of aeration, score 2 = moderate loss of aeration, score 3 = severe loss of aeration. The most severe pattern observed in an area is normally retained. Score 0 is intended when the “A-pattern” is visualized (i.e., A-lines with sliding) or < 3 well-spaced B-lines per scan; scores 1 and 2 are differentiated by quantity and/or quality of artifacts (see statement 4.2); score 3 is intended when a large consolidation is visualized (see statement 4.3, as well as Fig. 3 for adults and Fig. 4 for paediatric and neonatal patients). This four-step scale is the only score compared to quantitative CT, which is considered the gold standard measure for global and regional lung aeration measurement [6, 18–20, 65].

Comparison to CT scan is mostly unfeasible for the paediatric and neonatal population for safety reasons; only one study compared a 6-step LUS aeration score to quantitative CT in a very small mixed ICU paediatric population, finding a moderate correlation, mostly with no significant difference in lung density between scores, supporting that a semiology different from the 0–3 score should not be used [63]. Several studies have instead been

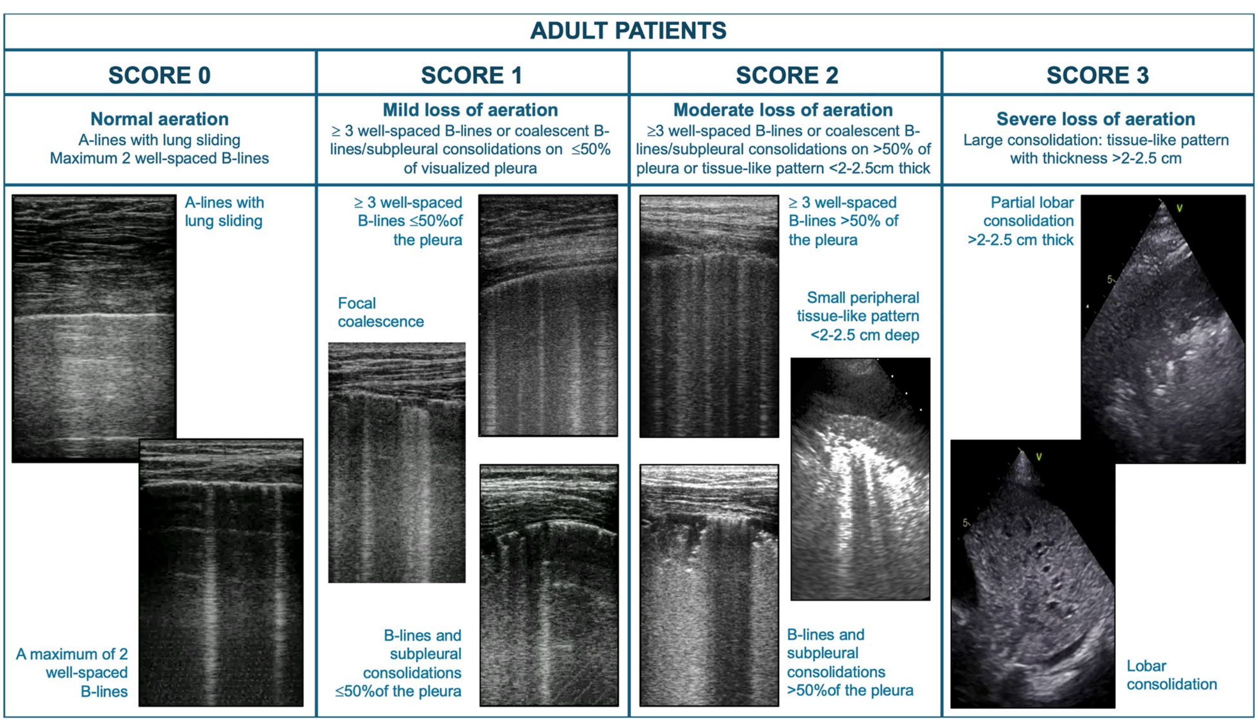

Fig. 3 Identification of the progressive aeration loss considered for the calculation of the lung ultrasound (LUS) aeration score. Illustrative examples in adult patients

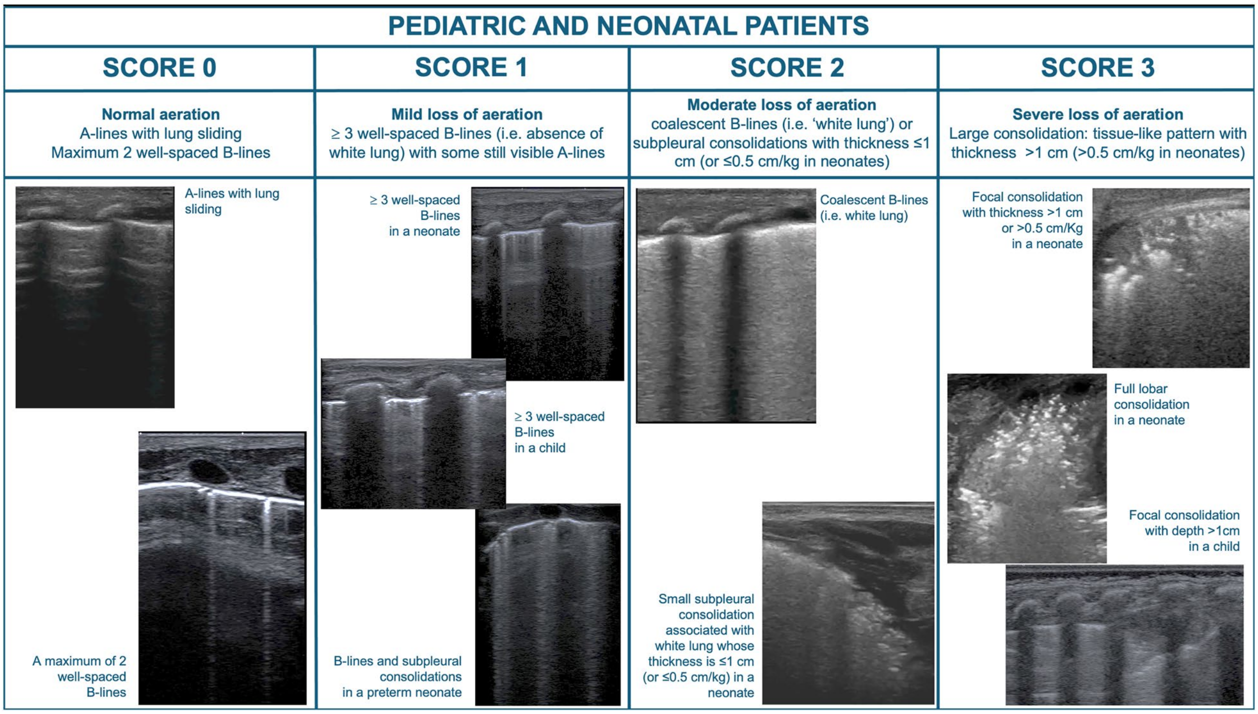

Fig. 4 Identification of the progressive aeration loss considered for the calculation of the lung ultrasound (LUS) aeration score. Illustrative examples in paediatric and neonatal patients

performed in newborns and infants comparing the 4-step LUS aeration score to EVLW [71, 72], or surrogates of lung aeration/function as gas exchanges measurements [34, 44, 45, 73–75], respiratory system compliance [42], surfactant adsorption [41], and airway resistances in restrictive and obstructive-restrictive neonatal respiratory failures [76]. Finally, this scale correlated with the degree of lung inflammation and surfactant function in RDS and meconium-induced NARDS [77, 78]. Consistent validation data are available in children beyond the neonatal age [79, 80]. Moreover, this 4-step scale was more sensitive and specific than chest X-rays (CXR) to detect aeration loss in patients with bronchiolitis [81].

STATEMENT 4.2: To distinguish between score 1 and 2 (i.e., mild vs. moderate loss of aeration) of the 0–3 scale, two approaches have been proposed: coalescence-based and quantitative-based. In adults, the quantitative-based approach outperforms the coalescence-based in terms of assessment of aeration, correlation with CT/EVLW and interobserver agreement.

RATIONALE: Two approaches to distinguish mild and moderate loss of aeration have been proposed: a coalescence-based (score 1 identified by ≥ 3 well-spaced B-lines *versus* score 2 identified by coalescent/crowded B-lines [18, 19, 22, 26, 34]) and a quantitative-based system (score 1: ≥ 3 well-spaced B-lines or coalescent B-lines/subpleural consolidations occupying ≤ 50% *versus* score 2: > 50% of the visualized pleura, Fig. 3) [20, 24, 28, 29, 82]. Both approaches were validated with quantitative CT [19, 20], but head-to-head comparison showed that the quantitative-based approach outperformed the coalescence-based in terms of CT aeration assessment [6], correlation with EVLW [29], and interobserver agreement [28]. The quantitative-based approach outperformed B-lines counting in terms of correlation with focal lung density assessed by quantitative CT or EVLW [20, 29]. In paediatric and neonatal patients, specific data are lacking and only the coalescent-based approach has been applied so far [34, 44, 45, 52, 55]; when evaluating B-lines in children and neonates, it would also be important to consider on how many intercostal spaces the assessment is done, and which probe frequency is used [61]. Further research is needed to clarify these issues in paediatrics and neonatology.

STATEMENT 4.3: The score 3 (severe loss of aeration) is attributed when a large consolidation is detected. To this aim, consolidation size can be quantified by measuring the distance from the pleural line to its deepest edge (> 2–2.5 cm in adults; > 1 cm or > 0.5 cm/kg in neonates).

RATIONALE: Almost all studies generally define lung consolidations as "tissue-like" areas, and with/without air-bronchograms. In one of the initial validation studies against quantitative CT, score 3 was attributed whatever the size of the tissue-like pattern, resulting in a substantial overestimation of loss of aeration [19]. In a subsequent analysis, a size threshold was applied by measuring the depth of the tissue-like area from the pleural line to its deepest edge (score 3 only if depth > 2.5 cm). This size threshold improved the correlation with quantitative CT and lung density for score 3 almost always corresponded to non-aerated tissue [6]. A similar approach was adopted in a study comparing LUS aeration score and focal tissue density assessed by CT: consolidations > 2 cm correlated to higher density [20].

Subpleural consolidations are defined as small juxtapleural echo-poor images with deep irregular boundaries [1]. In the quantitative-based score, subpleural consolidations are considered together with B-lines to give score 1 or 2 in adults [28]. With this approach, the correlation between LUS aeration score and lung density at CT or EVLW is very good [6, 19].

In neonatal and paediatric patients, most studies conventionally (i.e. without formal validations) consider score 3 when consolidation depth is > 1 cm, although no comparison to quantitative CT is feasible in these populations. However, two studies specifically investigated the consolidation size in these populations. An Australian single-centre study defined 0.5 cm as the best cutoff but only used as a reference CXR, which cannot substitute CT scan as gold standard [73]. A multicentre, observational study enrolling neonates with different types of neonatal respiratory disorders, described consolidation size to be always > 1 cm and > 0.5 cm/kg [83]. Therefore, considering the wide patient weight variation observed in the NICU (i.e. 400–4000 g) it is advisable to give a score of 3 taking patient weight into consideration (i.e. when either its depth is > 1 cm or > 0.5 cm/kg) [83]. There are no studies about this issue in children beyond neonatal age.

QUESTION 5: In ICU-admitted patients, is the automated/assisted score calculation reliable and useful?

STATEMENT 5.1: Automated/assisted quantitative lung ultrasound has the potential to reduce inter- and intra-observer variability and create a unique quantification system.

RATIONALE: Inter-rater agreement in B-lines analysis may be dependent on the raters' expertise [84, 85]. This variability can be explained by ultrasound pattern variations over the respiratory cycle, aeration heterogeneity, ambiguous scoring definitions and variable ventilator settings. Image processing/analysis and computer-aided techniques have become a major research topic since automated/assisted LUS aeration score might achieve a more objective, operator-independent and quick assessment [13]. The automated/assisted LUS aeration score reflects the air-to-fluid ratio irrespective of B-lines and identifies the ultrasound attenuation not only dependent on absorption and reflections, but also on beam scattering (both Rayleigh scattering, where structures smaller than the ultrasonic length are encountered and no B-lines are generated, and Tyndall scattering, where B-lines appear) [29]. In post-cardiac surgery intensive care, automated/assisted LUS aeration score was tightly correlated with pulmonary capillary wedge pressure and EVLW, independently of PEEP and only required 5 min to be calculated [64]. Furthermore, automated/assisted LUS aeration score helped non-expert clinicians to be quicker and improve their skills and confidence [86]. In a neonatal population with mixed respiratory conditions, automated/assisted LUS aeration score showed a significant correlation with oxygenation metrics [75]. Interestingly, both in adults and neonates, the LUS aeration score computed by an expert operator showed a higher correlation with the reference technique than the automated/assisted score [29, 75]. Thus, technical advancements are still needed to make automated/assisted LUS aeration score widely applicable in clinical practice: more data are available in the electronic supplementary material 7.

Question 6: for ICU clinicians, which is the minimum required training to correctly compute the lus aeration score?

STATEMENT 6.1: Theoretical-practical training in LUS varies widely but enhances participants' knowledge regardless of patients' age.

RATIONALE: Multiple training modules are available for LUS. A systematic review showed that both online modalities and traditional methods improved theoretical and practical knowledge although with substantial heterogeneity [87]. There is an urgent need for dedicated studies to develop well-structured critical care ultrasound training programs, including quantitative LUS (Fig. 5). Virtual reality tools may have a role in standardization and in objective assessments of trainees' competencies [87]. The only paediatric/neonatal data are represented by a survey demonstrating that an online training program increased the trainees' diagnostic confidence [88], but, given the shared semiology, it seems reasonable to apply the adult data to paediatric patients as much as possible.

STATEMENT 6.2: In adults, the minimum practical training required to accurately compute the LUS aeration score is 25 supervised examinations. In paediatrics, less precise data are available; from 2 weeks to 3 months of supervised practice seems to be a reasonable training timeframe.

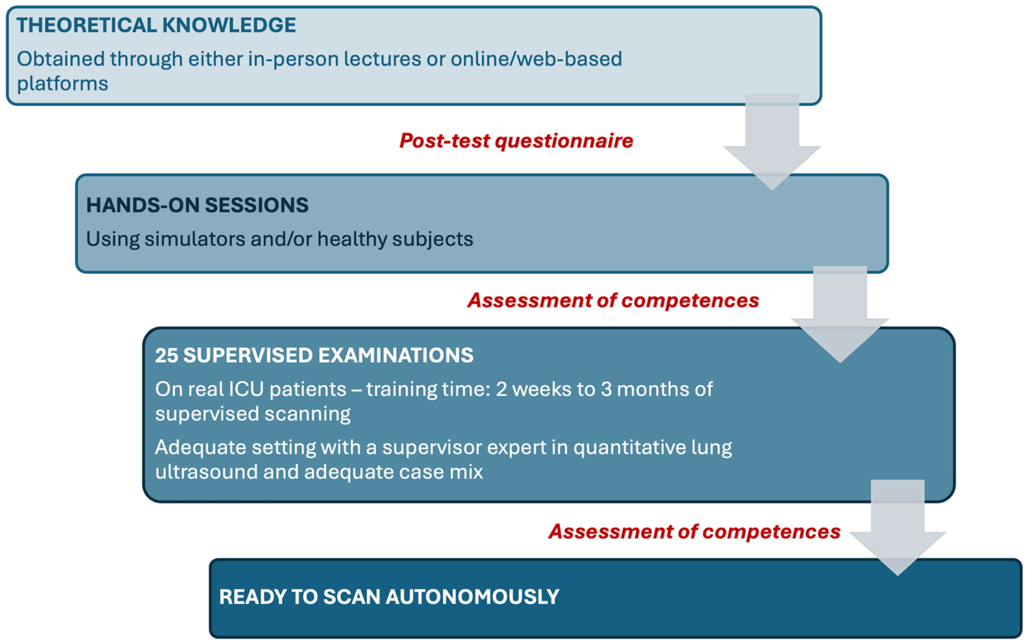

Fig. 5 A proposal of a systematic approach to quantitative lung ultrasound training. So far, no theoretical or practical tests for the assessment of competences have been validated in adults or paediatrics. The benefit of using simulators *vs.* healthy subjects in paediatrics is unknown. Twenty-five supervised examinations demonstrated to be sufficient to reach an agreement between trainees and experts in the computation of the lung ultrasound score in adults; in lack of similar data in paediatrics, from 2 weeks to 3 months of supervised practice seems to be a reasonable training timeframe

RATIONALE: Only one study focused on training in LUS aeration score computation comparing trainees and experts: a concordance between the two was achieved after 25 supervised ultrasound examinations, with a median of 56 training days [89]. A similar number of exams has been proposed by the same authors for the acquisition of basic LUS competences [90]. Less accurate data are available for paediatric/neonatal patients; in general, 2 weeks to 3 months of training with active supervised scanning have been described [90–92]. The activity of the training centre should also be considered to offer an adequate case mix to the apprentice (Fig. 5) [93, 94].

STATEMENT 6.3: The interobserver agreement between experts in LUS aeration score computation is near perfect irrespective of patients' age.

RATIONALE: The inter-rater agreement for the LUS aeration score calculation is good in neonatal/paediatric [91, 92, 95] and very good in adult patients [96]. The agreement can be reduced for beginners, when sub-optimal probes and frequencies are used [60], but is improved by training reaching an almost-perfect level between expert clinicians [19, 28, 89, 97].

Question 7: in patients admitted to ICU for respiratory failure, is LUS aeration score reliable, safe and suitable to assess and monitor lung aeration and the severity of the disease compared to other imaging (e.g., CT, CXR, electrical impedance tomography – EIT) and non-imaging (e.g., EVLW assessment) techniques?

STATEMENT 7.1: Quantitative LUS can reliably assess and monitor lung aeration and severity of the disease in critically ill adults, children and neonates.

RATIONALE: In mixed adult ICU populations, as well as in ARDS and COVID-19 patients, moderate to high correlations were found between quantitative LUS and quantitative CT evaluation, CT severity scores, EVLW and their variations (in electronic supplementary material 8: table of observational studies comparing quantitative LUS to other techniques); LUS aeration score was highly reliable to assess the severity of the disease in critically ill patients and to monitor lung aeration variations [18–20, 22, 24–26, 54, 65, 66, 68, 98–107].

Similar evidence is available in paediatrics, although CT is less used and limited to case series of neonates with lung malformations or children with COVID-19 [30, 108]. However, the LUS aeration score significantly correlated with surfactant function, lung mechanics, conventional radiology, clinical severity scores and gas exchanges metrics; moreover, the LUS aeration score reliably assessed the severity of the disease in children/neonates with various respiratory disorders, in different settings and respiratory assistance, from non-invasive to extra-corporeal support [33, 34, 41, 42, 44, 45, 47, 53, 55, 58, 76, 78–80, 109–112].

STATEMENT 7.2: Evidence about quantitative LUS safety in terms of nosocomial infections and side effects is limited.

RATIONALE: No specific evidence could be identified concerning the safety of the use of quantitative LUS in ICU in patients of any age – i.e. risk of nosocomial infections and cross-contamination – but caution should be applied, as ultrasound equipment can be a potential bacterial reservoir and source of cross-contamination [113, 114]. Surfaces beyond the ultrasound probes are particularly at risk, e.g. keyboards, handles, and ultrasound gel. Manuals are now available to systematically tackle the issue of infection prevention linked to ultrasound.

STATEMENT 7.3: Quantitative LUS is suitable and little time-consuming to assess and monitor lung aeration in adults, children and neonates.

RATIONALE: Quantitative LUS saves time in assessing the severity of respiratory diseases and monitoring lung aeration changes, in adults, children and neonates, when compared to traditional imaging, sparing radiation exposure [115, 116]. After standardized training, the median time to calculate the LUS aeration score was 8 and 10 min for experts and trainees, respectively [89]. In other studies, experts were even faster (3 to 4.5 min) [117]. Similarly, in paediatric and neonatal patients LUS calculation lasted from 7 to 20 min and was significantly faster than CXR [118].

QUESTION 8: In patients admitted to ICU for respiratory failure, is a quantitative approach reliable and suitable to define ARDS and its phenotype (focal/non-focal)?

STATEMENT 8.1: LUS associated with clinical parameters is reliable and suitable to define ARDS in adults, children and neonates when both LUS aeration score and pleural abnormalities are considered.

RATIONALE: In ICU adult patients undergoing mechanical ventilation, quantitative LUS is a reliable tool to diagnose ARDS compared to the Berlin definition [82, 119]. The Kigali modification of the Berlin definition originally proposed the bilateral presence of at least three B-lines (score 1–2) or consolidations (score 3) as the ultrasound definition of ARDS [120]. This approach was integrated into the New Global definition [121]. However, these criteria are sensitive but not specific for ARDS diagnosis [82, 119], resulting in a higher frequency of ARDS [122]. Adding qualitative LUS criteria, especially pleural line abnormalities, improved its specificity [82, 123, 124]. It seems reasonable to extrapolate these data to diagnose paediatric ARDS (PARDS) and neonatal ARDS (NARDS). The current PARDS and NARDS definitions (i.e. PALICC and Montreux definitions, respectively) have not included LUS, but explicitly allow physicians to use ultrasound rather than conventional radiology, if enough expertise is available [125, 126]. Only a few small studies have reported PARDS and NARDS diagnosis using LUS and did not focus on the diagnostic accuracy for the syndrome [127, 128], thus its use cannot be generalized yet. It is crucial to remember that for ARDS diagnosis the ultrasound findings should always be assessed in conjunction with the other diagnostic criteria as dictated by current definitions.

STATEMENT 8.2: Quantitative LUS may be reliable and suitable for the ARDS phenotyping and the classification of lung morphology in adult patients.

RATIONALE: Classification of lung morphology has the potential to improve the outcome of adult ARDS patients, but only if the morphology is correctly identified. Two studies showed that quantitative LUS could accurately classify lung morphology compared to CT: one showed that an anterior score ≥ 3 was sensitive and specific for non-focal lung morphology, and the other found that the anterior regions had the most discriminative value but that the accuracy could be improved by a validated decision tree including lateral and posterior fields [37, 124, 129]. There is no data regarding this matter in the neonatal/paediatric population, but it has been demonstrated that lung heterogeneity can be classified with LUS in neonates with common respiratory disorders [36].

Question 9: In patients admitted to ICU for respiratory failure, is lus aeration score reliable and suitable to indicate and interpret specific diagnostic and/or therapeutic procedures?

STATEMENT 9.1: LUS aeration score is reliable and suitable to indicate surfactant replacement in neonates with RDS, ensuring its timely administration, and to monitor its effectiveness.

RATIONALE: In several prospective diagnostic accuracy studies and in their meta-analyses, the LUS aeration score calculated in a simplified way (see above statements 2.2–2.3 and Fig. 1) accurately predicted surfactant need in neonates irrespective of their gestational age; the cut-off with optimal accuracy was approximately 8, while the maximum sensitivity to use as a screening in late preterm and term neonates was 4 [45, 46, 49, 74, 130–137]. The diagnostic accuracy is not changed by maternal chorioamnionitis [138], and is sufficient to reduce late and less effective surfactant administration.[139, 140]. After surfactant treatment, improvements in oxygenation and LUS aeration score (although with a certain variability due to the underlying disease and the different ultrasound and ventilatory protocol), imply that LUS may be useful to the monitor the effect of surfactant [43, 55, 74].

STATEMENT 9.2: Quantitative LUS is reliable and suitable to assess EVLW and guide fluid therapies in adults, children and neonates.

RATIONALE: In adults, different quantitative LUS approaches – including the LUS aeration score – resulted in reliable and suitable assessment and monitoring of changes in air/fluid ratio compared to EVLW, allowing the assessment of fluid tolerance [105, 106, 141, 142]. LUS aeration score allowed early recognition of fluid accumulation in ARDS [143]. In patients with fluid overload or cardiogenic pulmonary oedema, a score based on B-lines only was reliable and suitable to monitor the effectiveness of fluids removal, with diuretics or continuous renal replacement, both in adults and children [144, 145]. Several studies conducted on neonates with or without cardiac disorders and in different settings reported significant correlations between LUS aeration score and EVLW [146–151]. The score can also reliably monitor the effect of diuretics in infants with evolving BPD [152].

The integration of LUS findings with other ultrasound techniques may further improve the assessment [153].

STATEMENT 9.3: There is no evidence supporting quantitative LUS to indicate and monitor bronchodilators.

RATIONALE: No study investigated quantitative LUS to indicate bronchodilators. In one observational study LUS aeration score decreased after bronchodilators in < 50% of children with bronchospasm. [154]

STATEMENT 9.4: In adults and children beyond the neonatal age, LUS aeration score may be reliable and suitable tool to prescribe, monitor and tailor respiratory physiotherapy.

RATIONALE: LUS aeration score accurately detected changes in lung aeration associated with respiratory physiotherapy in patients under mechanical ventilation [155], but not in COVID-19 patients [156]. Moreover, quantitative LUS significantly helped to personalize the physiotherapy in adults and children [157]. In paediatric/neonatal ICU respiratory physiotherapy is not supported by strong evidence and is usually performed only on a case-by-case evaluation: no recommendation can be provided about the role of quantitative LUS in this regard.

STATEMENT 9.5: LUS aeration score is reliable and suitable to assess PEEP-induced recruitment in adults; limited evidence is available in children and neonates.

RATIONALE: The variations of LUS aeration score correlated with PEEP-induced air-recruitment (i.e., inflation of previously aerated alveoli) as measured in adults by pressure–volume curves and end-expiratory lung volume [26], recruitment to inflation ratio [158], EIT [159], and gas-exchange [160]. LUS aeration score variations did not correlate with tissue recruitment (i.e., reaeration of previously collapsed alveoli) as measured by quantitative CT [19]. While anterior fields seem most informative for recruitability in ARDS patients [26, 37], the loss of aeration and its PEEP-induced changes were mainly in posterior fields when related to atelectasis in ventilated adults with brain injury[161] or after general anaesthesia [162–164]. The experience in children is limited to perioperative intensive care: LUS aeration score successfully guided recruitment manoeuvres undergoing various surgical procedures helping to reduce atelectasis and improve clinical outcomes [59, 62, 165–169]. In neonates two preliminary small studies suggested an improved clinical outcomes with LUS-guided alveolar recruitment under invasive or non-invasive ventilation [170, 171]. A third larger study has been conducted in neonates with RDS or transient tachypnoea supported with nasal mask-delivered CPAP [172]. Results show that the LUS aeration score (in its extended version – see statement 2.3, Fig. 1) captures the effect of increasing CPAP from 4 to 8 cmH_2O, but this seems less visible and clinically meaningless in neonates with RDS and for CPAP > 6 cmH_2O [172]. There are no studies about alveolar recruitment in PARDS and NARDS. Nonetheless, given the absence of other means to monitor recruitment and the data produced studying other respiratory interventions (e.g., surfactant, diuretics), the authors suggest that the technique might reliably guide recruitment in children and neonates too.

STATEMENT 9.6: LUS aeration score is reliable and suitable to monitor the effects of prone positioning, in patients of any age.

RATIONALE: The aeration changes assessed by the LUS aeration score correlated with the increase of end-expiratory lung volume measured by nitrogen washout/washin technique [173] and with clinical immediate and long-term response to prone positioning in ARDS in most studies, [31, 173, 174] including COVID-19 patients [160, 175, 176]. A single study didn't find a correlation between reaeration score and oxygenation response, although showing a significant reaeration of posterior fields [31]. A single-centre trial demonstrated that lateral positioning combined with periodic ventilator sighs reduced the LUS aeration score while improving oxygenation and lung mechanics [177]. In critically ill neonates with RDS, NARDS and evolving BPD a decrease in LUS aeration score (using its extended version – see statement 2.3, Fig. 1) was observed after 6 h of pronation [53]. This was associated with improved gas exchange, with a reversal of effect by shifting the position and a greater benefit in BPD patients [53], probably due to their greater lung heterogeneity [36]. The time spent on a given position influences the improvements in lung aeration and function; however, the minimum time needed to achieve relevant benefits is unclear.

STATEMENT 9.7: To date, there is no evidence to support quantitative LUS for assessment and monitoring of lung hyperinflation; a reduced sliding in the anterior fields may suggest hyperinflation, but limited data are available.

RATIONALE: There is no evidence to support quantitative LUS to assess lung hyperinflation. Only scarce preliminary data are available. They report a qualitative assessment of overdistension using a prominent A-pattern with reduced lung sliding [178].

QUESTION 10: In patients admitted to ICU for respiratory failure, is quantitative LUS reliable and suitable to predict weaning failure and other clinical outcomes?

STATEMENT 10.1: LUS aeration score combined to clinical parameters is reliable and suitable to predict weaning and extubation failure in adults, children and neonates.

RATIONALE: In several observational studies in adults, a higher LUS aeration score accurately predicted weaning failure [38, 39, 179–182]. The loss of aeration is the final common pathway of multiple physiopathological mechanisms, including but not limited to weaning-induced pulmonary oedema [39, 183]. While baseline values were not always significant, the LUS aeration score after a successful spontaneous breathing trial was more accurate: in a general ICU population, a LUS aeration score > 17 identified patients at high risk of extubation failure [39, 179, 182, 184]. A score calculated on anterior or antero-lateral regions performed as well as a complete examination (high risk > 5) [38, 39]. Despite heterogenicity in scores and weaning protocols across the studies, the accuracy for failure identification is consistently very high [38, 39, 181]. Similar data are reported in children [185, 186], and neonates [187, 188]. LUS detects the severity of aeration loss; therefore, it cannot be used to predict extubation failure due to other causes (e.g. impaired airway control or respiratory drive). A combination of lung, diaphragm and cardiac ultrasound may improve accuracy [17, 38].

STATEMENT 10.2: LUS aeration score is reliable and suitable for early prediction of BPD in preterm infants.

RATIONALE: Several multicentre studies investigated quantitative LUS to monitor the progression of respiratory morbidity and predict BPD or moderate-to-severe BPD [51]. A pragmatic diagnostic meta-analysis of these studies found good sensitivity and specificity when the score is calculated (in its simplified or extended version) either at 7 or 14 days of postnatal age, irrespective of gestational age, sex and antenatal steroid prophylaxis [51]. The diagnostic accuracy is similar between the two-time points. It is, however, recommended not to use the LUS aeration score to predict BPD before one week of age since it may still capture the loss of aeration due to perinatal lung injuries. The simplified score performed slightly worse than the extended one, but the difference is probably clinically meaningless (see also statements 2.2 and 2.3, Fig. 1). The thresholds associated with the highest global accuracy to predict BPD are approximately between 5 and 7 and between 10 and 13 for the simplified and extended approach, respectively [51]. Thresholds for the prediction of moderate-to-severe BPD should be slightly higher but are more uncertain as less data are available for this purpose. Further studies are needed to explore the usefulness to select patients for new experimental BPD therapies as well as to distinguish, characterise and predict different types of BPD.

STATEMENT 10.3: LUS aeration score seems reliable and suitable to predict the need, monitor the efficacy and predict the failure of non-invasive respiratory supports in children and neonates; scarce data are available in adults.

RATIONALE: LUS aeration score accurately predicts the escalation from standard oxygen therapy to non-invasive/invasive ventilation in children [30, 189], and in neonates [190, 191]. More data are needed in adults: a decreased LUS aeration score correlated with the success of high-flow nasal cannula in thoracic trauma and non-invasive ventilation in COVID-19,[192–194]. B-lines count did not correlate with non-invasive ventilation failure in onco-haematological patients [195].

STATEMENT 10.4: LUS aeration score may be associated with ICU mortality in adult COVID-19 patients and probably in non-COVID-19 acute respiratory failure; inconclusive data are available for length of mechanical ventilation, ICU and hospital stay.

RATIONALE: Most studies focused on ICU outcomes were performed on COVID-19 adult patients: higher LUS aeration scores upon ICU admission were associated with higher mortality; moreover survivors showed a downward trend and score accuracy was higher after 3–5 days [196–198]. A single study reported that LUS aeration score performed after 12 h of ICU admission accurately predicted the need for prolonged mechanical ventilation in a mixed ICU pediatric population [199]. Nonetheless, some contradictory data exist on mortality and other clinical outcomes as ICU/hospital length-of-stay or length of mechanical ventilation [200]. Besides COVID-19, the LUS aeration score accurately predicted mortality in mixed ICU-populations, shock and ARDS patients [105, 201, 202].

STATEMENT 10.5: Quantitative LUS is reliable and suitable to predict post-operative complications in adults and children.

RATIONALE: LUS aeration score performed upon ICU admission in surgical patients detected atelectasis and was associated with hypoxemia and prolonged respiratory support [164, 203, 204]. When performed after extubation, higher scores corresponded to increased risks of respiratory complications [163, 205]. No score improvement three days after thoracic surgery was suggestive of lung complications. [206] LUS aeration score detected the effectiveness of pre-emptive high-flow nasal oxygen after major gynaecological surgery [162]. In lung transplanted patients, the B-lines count outperformed conventional radiology in the early detection of primary graft dysfunction [207]. The technique performed similarly, in children undergoing cardiac surgery [186].

QUESTION 11: In NICU-admitted patients is lus aeration score reliable and suitable to diagnose lung/thoracic malformations or to confirm the prenatal diagnosis of lung/thoracic malformations?

STATEMENT 11.1: Qualitative LUS is suitable to diagnose/confirm the diagnosis of malformations, but its reliability and the role of quantitative LUS are unknown.

RATIONALE: Thoracic and lung malformations encompass various abnormalities such as congenital diaphragmatic hernia (CDH), congenital pulmonary airway malformation or lung sequestration that may be asymptomatic or present with severe respiratory failure. The diagnosis is usually made with prenatal ultrasonography and MRI and postnatal CXR or CT; LUS can be helpful too as malformations have been qualitatively described in some case series, although it should not be the only imaging technique before indication to any surgical procedure.[108, 208] CT scan remains the gold standard for most pulmonary malformations, albeit it is logical that the presence of malformations influences lung aeration and thus the computation of scores. Only one case series assessed patients with mild CDH before and after surgery using a modified non-validated score, with no comparison to any other imaging, which improved after the surgery [209]. In CDH patients the difference between the score calculated including or excluding the affected lung may significantly impact the score calculation: further studies are needed in this field.

QUESTION 12: In patients under mechanical ventilation, is quantitative LUS reliable and suitable to suspect and monitor ventilator-associated pneumonia (VAP)?

STATEMENT 12.1: In mechanically ventilated adults, an increase in LUS aeration score corresponding to a worsening of lung aeration is reliable and suitable to rise VAP suspicion when clinical criteria are met.

RATIONALE: In mechanically ventilated patients, the ultrasound assessment of lung aeration could contribute to the early diagnosis of VAP as a screening tool. In COVID-19 patients with VAP, LUS aeration score at VAP diagnosis was increased compared to the previous 48-72 h [210, 211].

STATEMENT 12.2: Scoring systems including clinical, microbiological parameters and specific LUS patterns are reliable and suitable to rule in/out VAP in adults; the dynamic linear-arborescent air bronchogram is the sign with the highest specificity. Similar clinical ultrasound scores have been reported in paediatric and neonatal patients; however, scarce data preclude firm statements about their generalized use.

RATIONALE: VAP represents a relevant issue in ICU patients, but there is no consensus on its diagnosis [211]. Clinical scores and radiologic criteria showed low specificity: the use of CT in critically ill patients is risky, and interpreting nonspecific new pulmonary infiltrates can be challenging. Microbiological criteria are accurate but may delay the prompt initiation of antibiotics. Multiparametric scores incorporating LUS signs alongside clinical and microbiological data outperformed individual measures with significantly higher accuracy in adults, children and neonates [56, 211–217]. Of note, these multiparametric scores integrate ultrasound features with high sensitivity (subpleural consolidations) or specificity (newly appeared dynamic linear-arborescent air bronchogram) and clinical/microbiological parameters [211, 212], but they are not based on LUS aeration score computation.

STATEMENT 12.3: Serial LUS aeration scores are suitable and reliable in the early detection of antibiotic-induced lung reaeration or extension of lung infection in case of antimicrobial success/failure in adults with VAP. Thus, the LUS aeration score may help in evaluating the duration of antibiotic therapy. This might also be possible in neonates, but scanty data are available.

RATIONALE: LUS aeration score can identify reaeration in patients responding to antibiotics potentially helping to tailor the duration of therapy. The score variations showed a significant correlation with procalcitonin on day 7 and with CT [18, 218]. A subgroup analysis of the only available neonatal study showed that the disappearance of LUS abnormalities is associated with antimicrobial success [216].

QUESTION 13: In hospitalized patients at risk of respiratory failure, is LUS aeration score reliable and suitable

for an early detection and monitoring of respiratory deterioration?

STATEMENT 13.1: Quantitative LUS is reliable and suitable for early detection and monitoring of respiratory deterioration and/or ARDS development in hospitalized adults, children and neonates with several conditions including respiratory disorders and renal failure.

RATIONALE: In homogeneous diseases as cardiogenic pulmonary oedema, a quantitative approach based on B-lines counting resulted in reliable for EVLW assessment and monitoring: the increase in B-lines was associated with an increased risk of clinical deterioration and death [219]. B-lines count monitored the respiratory conditions and the response to treatment in adult patients with chronic heart [220], or renal failure [221]. In children with congenital heart defects, the score is useful to classify the degree of pulmonary oedema which may have prognostic potential [186, 222]. Lung congestion 12-36h after the surgery correlated with longer cardiopulmonary bypass, need of mechanical ventilation and PICU stay [186]. PICUs and NICUs are often contiguous to sub-intensive or step-down/observational units and emergency or delivery room where quantitative LUS is often performed by the same intensivists. Therefore, these considerations easily apply to children and neonates, provided that physicians working in the various structures have enough expertise.

QUESTION 14: Is quantitative LUS reliable and suitable in specific clinical conditions?

STATEMENT 14.1—QUANTITATIVE LUS AND COVID-19: In association with physical examination and clinical criteria, the LUS aeration score is reliable and suitable for COVID-19 triage and severity assessment in adult patients. In paediatric and neonatal patients with COVID-19, quantitative LUS is similarly suitable but its reliability for triage and severity assessment is uncertain.

RATIONALE: LUS aeration score in non-intubated COVID-19 patients strongly correlated with CT severity score [104, 223, 224], and clinical outcomes [66, 225, 226], making it a valuable risk stratification tool [200, 227]. This has been confirmed in patients already or not yet admitted to ICU [193, 225]. Consistently, quantitative LUS was used to assess the severity of paediatric COVID-19. [228–231] as it was associated with severity biomarkers [127, 232, 233]. The reliability of quantitative LUS to assess neonatal COVID-19 in the first week of life may be reduced by the similar ultrasound appearance of other common perinatal lung injuries [234].

STATEMENT 14.2—QUANTITATIVE LUS AND PREGNANT PATIENTS: Quantitative LUS is reliable and suitable in pregnant patients, allowing the detection of cardiogenic pulmonary oedema, pre-eclampsia-related pulmonary oedema, SARS-CoV-2 pneumonia and others pulmonary complications.

RATIONALE: Quantitative LUS can be performed during pregnancy as in non-pregnant patients [235]. Due to pregnancy-related physiological changes, pregnant women are prone to develop pulmonary oedema, especially in pre-eclampsia detectable by a score based on B-lines counting [236, 237]. The technique allows the detection of increased EVLW associated with systolic/diastolic dysfunction [238]. During pregnancy, quantitative LUS can also provide useful information about SARS-CoV-2 pneumonia and its evolution as in non-pregnant patients [239, 240]. LUS aeration score performed at admission is useful to detect pulmonary complications such as pulmonary oedema, pneumonia, atelectasis and ARDS in critically ill parturient women with or without signs of respiratory distress [240]. However, there is limited evidence against CT scan as diagnostic accuracy gold standard in this patient group.

STATEMENT 14.3—QUANTITATIVE LUS AND CARDIOGENIC PULMONARY EDEMA (CPE): Quantitative LUS is reliable and suitable to detect CPE and indicate ICU admission in adults and probably in paediatric patients too.

RATIONALE: In adults, LUS is more sensitive than CXR in detecting CPE in the emergency departments (ED) [241–243], and its use is recommended by European Society of Cardiology guidelines [244]. Being CPE a homogeneous lung disease with increased EVLW, two methods based on B-line quantification have been mainly used: B-pattern positive/negative zones, mostly used in ED [245], and B-lines count [246]. They showed comparable reliability but B-pattern zones classification had higher feasibility and reproducibility [247]. B-lines scores correlated with EVLW [248], NT-proBNP [249], and oxygenation [21]. In adults with acute heart failure, B-lines scores have been used for risk stratification [246, 250], guiding treatments [251], monitoring [252] and prognosis [253]. An integrated echocardiography and LUS approach is recommended by the European Association of Cardiovascular Imaging to quantify the degree of pulmonary involvement, irrespective of aetiology [220]. In paediatrics, the LUS aeration score has been used for the prediction of hemodynamically significant patent *ductus arteriosus* causing pulmonary overflow in preterm infants, and the follow-up after its closure [151]. In infants with congenital heart defects, B-line scores have demonstrated a moderate correlation to EVLW and NT-proBNP [186, 254].

STATEMENT 14.4—QUANTITATIVE LUS AND ECMO: LUS aeration score is suitable to monitor lung

aeration changes in adult, paediatric and neonatal ARDS patients receiving ECMO; there are insufficient data for its reliability and prognostic value.

RATIONALE: The LUS aeration score was easily used to monitor lung aeration in adult ARDS patients receiving ECMO, with a progressive reduction of the score indicating gradual recovery [255, 256]. In COVID-19 patients on ECMO, the score monitoring was feasible, and its variations were associated with mortality [257]. Quantitative LUS was suitable to assess lung aeration in neonatal and paediatric ARDS supported with ECMO [258, 259]. and was associated with outcomes such as mortality and length of ICU stay [112]. In patients of any age, a decrease in LUS aeration score was associated with lower ECMO blood flow and outcome [111, 256, 255]. Further and larger studies are needed in ECMO patients, since the available studies are based on relatively small populations.

STATEMENT 14.5—QUANTITATIVE LUS IN LMIC: LUS aeration score is suitable in LMIC in critically ill adults, children and neonates but most of the available data are limited to non-ventilated patients.

RATIONALE: Serial LUS examinations were used to quantify aeration in adult patients with sepsis and severe malaria in Bangladesh, showing high feasibility and association with mortality in settings with limited ICU resources [260]. The LUS aeration score was feasible to assess lung aeration and detect pulmonary complications in non-intubated critically ill parturients in Sierra Leone [240]. The implementation of quantitative LUS in a NICU of a middle-income country was feasible in a dedicated study after a short training period, reaching a good inter-rater agreement between experts and beginners [92].

Discussion and conclusions

This consensus is the result of a unique interdisciplinary effort shared by adult and paediatric/neonatal intensive care experts. It provides a large number of statements on both technical aspects and clinical applications of quantitative lung ultrasound in adult, paediatric and neonatal critical care. The statements aim to serve as a guide for the implementation of quantitative lung ultrasound in everyday ICU clinical practice. Ours is a snapshot of current knowledge, however, as research is advancing, new editions of this work should be programmed once enough new evidence will be accumulated. Given the usefulness of quantitative LUS and its development potential, ESICM and ESPNIC are engaged in this direction with the aim to provide the strongest possible evidence-based guidance for intensivists around the world.

Despite we have deployed all efforts to apply the most rigorous methodology, we acknowledge some limitations. First, the panel is composed of a relatively small number of experts, since we applied restrictive criteria about intensive care clinical practice and research on quantitative lung ultrasound. This also implies that not all countries are equally represented since the expertise was considered an overriding criterion. However, we obtained a panel with a fair gender balance, at least one expert from LMIC (IC) and at least two experts with clinical/research expertise in LMIC (LP, MS). These strict pre-defined criteria also aimed to minimize as much as possible the selection bias of the panellists. Second, while the interdisciplinarity represents a strength of the present work, we decided that specialty-specific statements needed to be developed and voted by only a part of the panel, therefore, by an even smaller number of experts. Nevertheless, this concerns only a minority of statements, and this choice was needed to recognise and value the specific competence of each panellist given their different training. Third, no experts in other field of respiratory medicine (respiratory physiologists, pulmonologists, emergency physicians) or in other imaging techniques (EIT, CT) were involved; however, interdisciplinarity is guaranteed by experts in critically ill patients of different ages and this also allowed to provide practical recommendations for the daily ICU application of quantitative lung ultrasound from experts in this specific field. In such a group, a positive attitude toward ultrasound use can be expected. Fourth, being an experts' consensus and in the absence of a systematic review of literature with its grading, there is a risk that unconsciously panellists gave priority to some articles over others based on their opinions, clinical experience and interests in LUS; a certain subjectivity in the choice of literature has to be expected. However, a systematic literature search is not mandatory in a Delphi process and the articles were not used to formally support the statements. Fifth, the numerous applications of qualitative lung ultrasound only (e.g., differential diagnosis of acute respiratory failure, guidance to pleural drainage, qualitative aspects of consolidation and effusions) are not detailed in this consensus since considered beyond its scope. Finally, as underlined by many statements, important questions must still be addressed and require future research. In fact, as for all consensus processes, further research will be needed particularly on some innovative techniques, as they hold the potential to modify the statements in the future. For instance, lung elastography [261] and speckle tracking technology [262] are promising tools for the quantification of lung sliding and overinflation. They have not been covered here but will likely be included in future editions of this consensus.

In conclusion, we provide the first consensus for the use of quantitative lung ultrasound in critically ill patients of any age: this work guides the use of the technique in adult, paediatric and neonatal intensive care and helps identify the fields where future research is needed.

Supplementary Information
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Authors' contribution
SM, DDL, AC and MRG contributed to the study conception and design. Material preparation and data collection were performed by all authors. Results were analysed by SM, DDL, AC and MRG. The first draft of the manuscript was by SM, DDL, AC, MRG and edited by all authors. All authors read and approved the final manuscript.

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Data availability
All the available data are shared in the supplementary material.

Declarations

Conflicts of interest
AAO received fees for lectures by Chiesi Farmaceutici, outside the present work. DGB received feed for lectures by Vygon SAS, dbMed Srl, SurveyMed srl, outside the present work. LDJB received grant by Longfonds, Innovative Medicine Initiative, Amsterdam UMC, Health Holland via Longfonds, ZonMW, Volition, Santhera, outside the present work; received consulting fees by Scailyte, outside the present work; is member of a paid advisory board for Sobi NL, Impentri, Novartis, AstraZeneca, CSL Behring, Aptarion, outside the present work. RGH received fees for lectures from Chiesi, outside the present work. MG received research grants from New Frontiers in Research Fund, GE HealthCare / BARDA and Fonds de Recherche du Québec, outside the present work; received fees for lectures by GE Healthcare, outside the present work. FM received fees for lectures from Hamilton Medical, outside the present work. A research agreement is active between the University of Pavia and Hamilton Medical, outside the present work. GN is a board member of the Australasian Society of Ultrasound in Medicine; received regular in-kind support from medical ultrasound companies with ultrasound machines for use during lung ultrasound training courses. LP received grants from, outside the present work. ITPA Wellcome grant PRT participated on a trial on the use of GHB in ICU patients; he is a member of the NVIC ultrasound committee, outside the present work. LZ received fees from General Electric Health care for lectures and ultrasound teaching, outside the present work. DDL has received research assistance and speakers fees from GE Healthcare, Medtronic, Vyaire, Getinge, Astra Zeneca and Chiesi Farmaceutici, unrelated to the present work. The other authors declare no conflicts of interest.

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